



Modelling Energy Supply of Future Smart Cities

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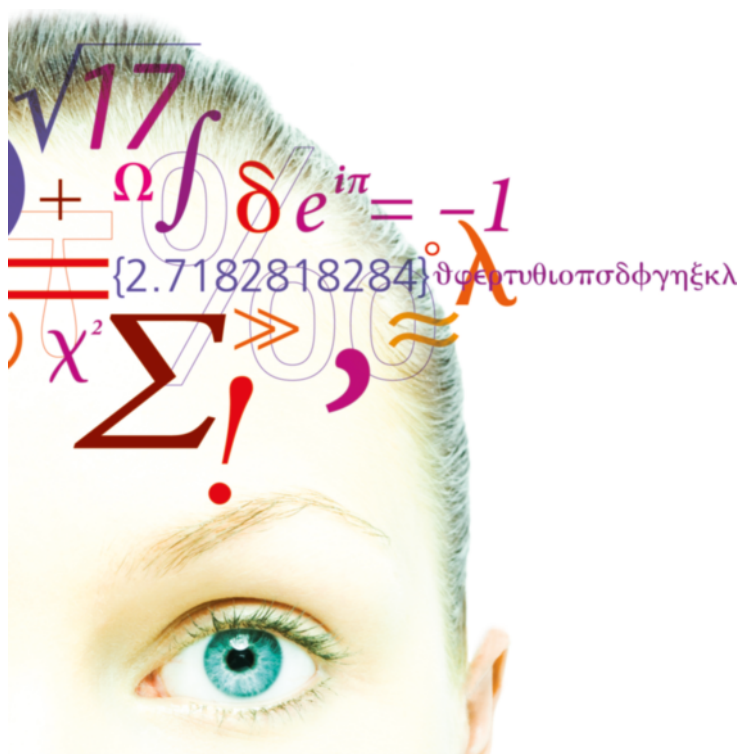
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Modelling Energy Supply of Future Smart Cities

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Mads Peter Sørensen

PhD Thesis
July 2018



Technical University of Denmark
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Modelling Energy Supply of Future Smart Cities

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Preface

This PhD thesis is the outcome of my diligent work that lasted for almost three years. I carried out this thesis mostly in the Copenhagen region, Denmark. However, a five months guest research stay in Singapore at *Nanyang Technological University* and a four months guest research stay in Colorado, the USA, at *National Renewable Energy Laboratory*, significantly contributed to my overall research results. Furthermore, during the PhD work, I have presented different topics connected to this thesis at nine conferences, which took place in four different continents, in order to disseminate results and obtain useful feedback. At those conferences, I co-authored 16 different conference papers; however, they were not included as an integral part of this PhD thesis.

Problems of air pollution in cities and adverse climate change effects can already be seen and felt across the globe. Several nations, such as the Nordic countries, and organisations, such as the European Union, decided to tackle these problems in a more structured way by dedicating more research funds and promoting new policies. However, complex interrelations between different stakeholders and technical experts with different backgrounds, the complexity of the topic of the energy transition itself, rising shares of urban population, changing patterns of energy supply from centralized to decentralized sources and swift technological development make the topic of energy supply of future cities a challenging and still under-researched one. The reasons mentioned above were my primary motivation for carrying out this PhD thesis, as well as for my move to Denmark, where I have found more support for the research on this topic. During the many smaller research projects in the last three years, that all contributed to this thesis in different ways, I have notably developed different skills such as critical thinking, pragmatic approach in handling different issues and obstacles, time management, handling stakeholders with different backgrounds and finally, writing concise and effective scientific papers.

The result of all the collaborations, conferences and guest research stays is this thesis. The core of this thesis is ten journal papers carried out during the last three years (nine of them already published and one submitted to a journal). In order to place the specific results from the enclosed papers in the broader context, the main text of the thesis presents a generic approach to the description of the energy systems, with a particular focus on energy supply of urban energy systems. It was written in a structured way, pointing to the most important aspects of the future energy supply, such as the role of the renewable energy sources, provision of flexibility, different energy storage types, the role of biomass in cities *et cetera*. Hence, the thesis is aimed for a wide range of stakeholders with interest in energy systems transition, urban energy systems, energy storage, the role of specific renewable energy technologies in a wider energy system and the role of different energy sectors in the overall energy system. It is further relevant for all the industry representatives who work in different energy sectors, governmental representatives who have to provide their citizens with actions for mitigating air pollution and climate change effects, as well as for those citizens that are generally interested in topics such as urban energy systems, urban transport, their potential engagement in the form of prosumers and air pollution. In order to make the points of the main text of the thesis scientifically supported, the enclosed papers (Paper 1 to Paper 10) are often referenced. Experts in specific fields, researchers on the topic of integrated energy systems, urban energy systems and others are invited to take a more thorough look at the relevant enclosed papers in order to examine the methods and data sets that were used.

Moreover, I have tried to cover as many aspects as possible of this holistic topic. Each specific subtopic (sections and subsections of the thesis) gives a short overview of the relevant results from the enclosed papers, followed by general conclusions and recommendations, comparison against the already existing literature and

the recommendation of the future work that is yet to be done. The literature comparison in the main text of this thesis mainly presents a comparison against the review papers of the specific topics and it is only an additional review, on top of the more detailed literature review of specific research topics which can be found in the attached papers.

In addition, although some subtopics, such as the role of biomass in cities and flexibility options that exist in the energy systems, were covered in great detail, there is indeed lots of work that has to be done, which was stated at relevant locations in the main text of the thesis. Moreover, I was maximally devoted to the overall research process, establishing collaborations with different research groups and visiting different research teams in order to further strengthen specific case studies through the joint work with local stakeholders in order to support the claims and findings of this thesis. As the ethics of publishing in the scientific community was the topic I have greatly cared of, I was always keen on checking the obtained data and analysis carried out, as well as taking care that the reached conclusions were supported by the data. Finally, I am fully confident that I did my best during this research process and I am glad that I know that any potential inaccuracy that will potentially be found in this thesis was unintentional. I wish for *you*, who is reading this thesis, to improve your knowledge in different aspects of the energy transition and that this thesis will encourage you to further continue the research on this topic and improve the results obtained in this PhD thesis.

In Copenhagen, the 12th of July 2018

Dominik Franjo Dominković

Acknowledgements

First and foremost, I wish to thank my family that was standing behind me in good and bad times. I always felt that I have firm support from them and they were always ready to help me when I needed them. To my parents *Zdenka* and *Ivan*, to my siblings *Ivana* and *Dario*, to my niece *Iris*, to my nephew *Lukas*, and all of my cousins: thank you a lot!

Second, I wish to give a big thank to my principal supervisor, Allan Schrøder Pedersen, whose supervision I have truly appreciated. He was very accommodating in my needs, provided me flexibility in my work and gave me lots of freedom in my work, which I was often seeking for. A further thank goes to my co-supervisors, Per Sieverts Nielsen and Mads Peter Sørensen, who gave me numerous valuable advice, suggestions and inputs in our discussions about many different topics. I have genuinely appreciated the support given by all three of you.

Moreover, as this thesis was the result of collaboration with many different parties, I have a long list of people whose help I appreciate. Goran Krajačić co-authored several of my papers, was always ready to discuss different emerging topics, issues and to initiate potential solutions. I further wish to thank Ivan Bačeković, currently a consultant at PwC Croatia, who co-authored three papers with me as a second author, helping me significantly during the research.

Furthermore, I wish to thank my supervisors during the external stays at NTU in Singapore and NREL in the USA. Alessandro Romagnoli (NTU) and Bri-Mathias Hodge (NREL). Thank you a lot for all the support that you gave to me, both with research, as well as with different adaptation issues. I also wish to express my gratitude to Greg Stark from NREL, who directly collaborated with me during my second external stay, prepared the data that I needed in my work and had several thoughtful discussions with me. I further wish to thank all other colleagues from NREL and NTU with whom I collaborated, who made my guest research stays as an amazing experience. Furthermore, I want to thank all the people that I met in both Singapore and the USA who were not my coworkers; you all made my guest research stays as memorable and invaluable experiences.

In addition, I further wish to thank my co-authors from different papers, to Viktorija Dobravec, who I formerly supervised during her master's thesis writing, to Mikko Wahlroos and Sanna Syri from the Aalto University, Finland, to Neven Duić, Antun Pfeifer, Tihomir Tomić, Daniel Rolph Schneider, Boris Ćosić and Tomislav Pukšec from the University of Zagreb, Croatia, to Nataša Markovska from the Macedonian Academy of Arts and Science, Macedonia, to Khairul Azahar Bin Abdul Rashid and Leong Kai Choong from the Nanyang Technological University, Singapore, to Dadi Sveinbjörnsson from PlanEnergi, Denmark, to Panagiota Gianniou, Marie Münster, Alfred Heller and Carsten Rode from the Technical University of Denmark and to Yu Jiang from the Wageningen University, the Netherlands. Thank you all for your valuable contributions to this thesis, your inputs are truly appreciated, and I hope that you enjoyed collaborating with me as much as I enjoyed collaborating with you.

I further wish to thank Henrik Madsen, who helped me in establishing collaboration with NREL, and to Nicolas Bernhardi from ProjectZero, who was keen on collaboration in several different research papers. Your contributions are appreciated.

Moreover, I want to thank all of my friends in Croatia, Denmark, Singapore, Colorado and all across the world, for the support and great fun during the PhD period. As it was so many people, I cannot name all of you, but I will always appreciate spending time with you and having you as friends.

Finally, I wish to thank all the people that were involved in the CITIES project, which also financed my PhD project. Many thanks to the Danish Ministry of Higher Education and Science that awarded me with the EliteForsk grant for the most talented young researchers in Denmark in 2017, worth 200,000 DKK, which financed my guest research stays and several conferences. I also wish to thank Otto Mønsted fund that co-financed ECOS 2017 conference in San Diego, California, the USA. I also wish to thank the representatives of Euroheat & Power network (and their district heating and cooling platform dubbed DHC+) that awarded me with the first prize for the best paper at the 4th International DHC+ Student Competition in 2016, which included a financial research contribution, too.

“Victory awaits him who has everything in order – luck, people call it. Defeat is certain for him who has neglected to take the necessary precautions in time; this is called bad luck.”

(The South Pole, by Roald Amundsen)

Abstract

The world has never been more urbanised, and urbanisation rates are still growing. Climate change on the one hand and air pollution, on the other hand, are resulting in adverse effects on the society. Nowadays, the majority of energy consumption occurs in cities, which are central parts of the overall economic activity. Constant changes in urban form, rising urbanisation rates, need for cleaner energy sources, variability in energy generation and rising economic output all contribute to the complexity of the urban energy transition. The solution for the future urban energy supply is further complicated by the interdisciplinarity of the urban transition. Energy engineers, mechanical engineers, civil engineers, architects and social scientists and others all have specific, and often different, objectives and approaches when focusing on the urban energy transition.

This thesis is focused on the technical aspects of the urban energy transition, the role of different technologies in the future urban energy supply, flexibility sources in urban energy systems, the role of district heating and district cooling in an urban context, the role of different storage types, the role of biomass in an urban context, energy transition of the mobility sector and optimal set-ups of future energy systems. It is a result of collaboration with many different researchers, industry and institute representatives. In order to deal with the energy transition in different contexts and case studies, three different models were used in this PhD thesis, both simulation and optimisation ones. One linear optimisation model was developed as a part of this thesis, to allow for specific modelling of different storage types, flexibility technologies, demand-response techniques and relations between different energy sources and technologies.

Results of several different case studies, from three different continents, showed that the urban energy transition is possible in different locations, albeit with different optimal mixes of different technologies. An important aspect that connects all the solutions is the need for integrated and holistic energy planning, as the sectoral integration of urban energy systems provides the flexibility needed for integrating large shares of variable renewable energy sources. Variable renewable energy sources can be integrated into the energy sources via different flexibility techniques: different storage types, import/export of electricity over the system boundary, demand-response technologies and power-to-heat and power-to-gas technologies. All four flexibility options were addressed in this PhD thesis and quantitatively evaluated. Optimal shares of thermal energy storage were usually higher than the capacity of other storage types. Urban energy systems integrated with the surroundings of a city, contrary to the notion of a self-sustainable city, yielded significant savings in socio-economic terms. Different demand-response technologies were tested in this thesis, and they all had a role in an optimal urban energy system of future: flexible demand for electricity in industry and buildings, as well as flexible district heating demand. The latter was achieved in this thesis by utilising thermal building mass for storage, with and without preheating, depending on different scenarios. It was further shown that district cooling could play a significant integrating role of variable renewable energy sources, in a similar manner to district heating. Nevertheless, it was also shown what the optimal levels of energy efficiency measures in terms of socio-economic costs in the urban context are, and what the optimal shares of individual and district energy supply in an urban context are.

The energy transition of the transport sector proved to be challenging. It was shown that everything that can be electrified should undergo electrification. However, parts of the transport sector that cannot be directly electrified will impose significant energy demand on the system. Several alternatives were investigated, and both biofuels and synthetic fuels produced via electrolyzers and synthesis proved to be challenging regarding sustainably utilising available resources.

The role of biomass in future urban energy systems was one of the core aspects of this thesis. Although disputed by different scientific articles, as discussed in this PhD thesis, the burning of biomass is often counted as a carbon-neutral source, if the total amount of living biomass compared to the previous year is not decreasing (e.g. the European Commission and the US Environmental Protection Agency follow this approach). Biomass can be further utilized for dispatchable biomass power plants. It can also be used for cogeneration plants and heat-only boilers, as well as for biofuel production. Papers that focused on the large-scale case studies in this PhD thesis showed that biomass demand will be significant in the future and it will be essential to constrain its excessive use that would make biomass unsustainable regarding climate change. Worryingly, biomass can be performing poorly regarding air pollution (SO_x, NO_x and particulate matter emissions), resulting in negative externalities imposed on the society, which was discussed in this PhD thesis. When seeking for the climate-friendly solution in terms of CO₂ emissions, it is important not to neglect the aspects of the air pollution.

Furthermore, it was shown that power-to-heat and power-to-gas-to-power technologies could play an important integrating role between different energy sectors in the future urban energy systems. A significant contribution from this PhD thesis was to quantify the potential of electrolyzers and fuel cells from the system point of view.

This PhD thesis provided several solutions for urban energy transition from the technical point of view, detected important interactions between different energy sectors, pointed to the usually less emphasised problems and opened several questions for future research, among others the energy transition of the heavy transportation modes and the assumption of carbon neutrality of biomass. This thesis will hopefully contribute to the discussion on urban energy transition, the role of different storage types, air pollution in cities and the modelling approach(es) of urban energy transition.

Resumé

Verden har aldrig tidligere været så urbaniseret som nu og urbaniseringshastigheden ser ud til at stige fremover. Samtidig har klimaændringer og luftforurening negative effekter på samfundet. Størstedelen af verdens energiforbrug sker i byer, som har central betydning for den samlede økonomiske aktivitet. Konstante ændringer af byernes form, stigende urbaniseringshastighed, behov for renere energikilder, variabilitet i energiproduktion og generelt stigende økonomisk aktivitet bidrager alt sammen til en betydelig kompleksitet af byernes overgang til vedvarende energikilder. Løsningen for den fremtidige energiforsyning til byer kompliceres yderligere af interdisciplinære behov i forbindelse med deres udviklingen. Energiingeniører, mekanikingeniører, bygningsingeniører, arkitekter og socialvidenskabelige eksperter såvel som andre har således alle særlige – men ofte forskellige – fokusområder, når de ser på byernes energimæssige udvikling.

Denne afhandling fokuserer på de tekniske aspekter af byers fremtidige energiomstilling, rollen for forskellige teknologier i byernes energiforsyning, kilder til fleksibilitet i byernes energisystem, rollen for fjernvarme og – køling i en bymæssig sammenhæng, forskellige muligheder for energilagring, udnyttelsen af biomasse i byer, transportsektorens energiomstilling samt optimale muligheder for energisystemets sammensætning. Afhandlingen er resultatet af samarbejde med mange forskellige forskere samt repræsentanter for industri og institutverden. For at arbejde med energiomstilling i forskellige sammenhæng og i forskellige tilfælde, er tre forskellige modeller blevet anvendt i denne PhD afhandling, omfattende såvel simulerings- som optimeringsmodeller. En lineær optimeringsmodel blev udviklet som en del af afhandlingen for at muliggøre specifik modellering af forskellige lagre, fleksibilitetsteknologier, demand-response-teknikker og relationer mellem forskellige energikilder og teknologier.

Resultater af flere forskellige case studier fra tre forskellige kontinenter viste, at en ændring af byers energisystem er mulig på forskellige lokaliteter, om end baseret på forskellige optimale anvendelser af forskellige teknologier. Det vigtigste aspekt, der karakteriserer alle løsningerne, er behovet for integreret og holistisk energiplanlægning, fordi sektorintegrationen af det bymæssige energisystem tilvejebragte den fleksibilitet, der er en forudsætning for integrering af store mængder varierende, bæredygtige energikilder. De varierende vedvarende energikilder kan integreres i energisystemet ved hjælp af forskellige fleksibilitetsteknikker: lagring, import/eksport af elektricitet over systemgrænser, demand-response-teknologier og power-to-heat og power-to-gas teknologier. Alle fire fleksibilitetsmuligheder blev adresseret i denne PhD afhandling og evalueret kvantitativt. De optimale andele af termisk energilagring var sædvanligvis større end lagerkapaciteten af andre lagringsteknologier. Byernes energisystemer viste, hvis de blev modelleret i sammenhæng med deres omgivelser (i modsætning til "selvforsynende byer"), signifikante socioøkonomiske besparelser. Forskellige demand-response-teknologier blev afprøvet i PhD arbejdet og viste sig alle at have en rolle i et optimeret, fremtidigt bymæssige energisystem: fleksibelt el-forbrug i industri og bygninger såvel som fleksibel efterspørgsel på fjernvarme. Det sidste blev fundet ved at udnytte bygningers termiske masse med eller uden forudgående opvarmning, afhængig af forskellige scenarier. Det blev yderligere vist, at fjernkøling, kan spille en vigtig integrerende rolle for variable, vedvarende energikilder på samme måde som fjernvarme. Endvidere blev de optimale niveauer for teknologier til højere energieffektivitet i en bymæssig sammenhæng påvist med hensyn til socioøkonomiske omkostninger, ligesom den optimale balance mellem individuel og fælles energiforsyning blev beskrevet.

Omstilling af energiforsyning til transportområdet viste sig at være en udfordring. Det blev påvist at alt, hvad der kan elektrificeres, bør overgå til elektrificering. Men de dele af transportsektoren, som ikke umiddelbart kan elektrificeres, vil udgøre en meget betydelig efterspørgsel på energi. En del alternativer blev studeret og

både bio-brændstoffer og syntetiske brændstoffer produceret ved elektrolyse og efterfølgende kemisk syntese viste sig at belaste de tilgængelige vedvarende energiresourcer betragteligt.

Betydningen af biomasse i energisystemet i fremtidens byer var et af kerneaspekterne i nærværende arbejde. Selvom det fortsat er en diskussion, som også behandlet i dette arbejde, så betragtes forbrænding af biomasse ofte som en CO₂-neutral kilde til energi, hvis den efterladte, samlede *levende* biomasse ikke er faldende (som f.eks. nævnt af Europakommissionen og US Environmental Protection Agency). Biomasse kan benyttes i fleksible biomassefyrede kraftværker. Biomasse kan også benyttes i kraft-varmeværker, til ren varmforsyning eller til fremstilling af biobrændstoffer. Artikler, der har fokuseret på stor-skala case studier i denne PhD afhandling viste, at efterspørgslen på biomasse vil være betydelig i fremtiden og det vil være vigtigt at begrænse et uhæmmet forbrug, der kan gøre biomasse ikke-vedvarende med hensyn til klimaforandringer. Det er desuden bekymrende, at biomasse kan være forurenende i form af luftforurening (SO_x, NO_x og partikler) og dertil hørende (eksterne) økonomiske belastninger af samfundsøkonomien, hvilket også diskuteres i denne PhD afhandling. Hvis der søges efter klimavenlige løsninger mht. CO₂-emissioner, er det væsentligt ikke at negligere aspekterne af luftforurening.

Det blev yderligere vist, at power-to-heat- og power-to-gas-to-power-teknologier kan spille en meget vigtig integrerende rolle mellem forskellige energisektorer i fremtidens bymæssige energisystem. Et væsentligt bidrag fra denne PhD afhandling har været at kvantificere potentialet af elektrolyseanlæg og brændselsceller fra et systemsynspunkt.

Dette PhD arbejde har fra et teknisk synspunkt tilvejebragt adskillige løsninger med hensyn til byernes overgang til nye, bæredygtige energisystemer, fundet vigtige vekselvirkninger mellem forskellige energisektorer, påpeget sædvanligvis oversete problemer og stillet adskillige spørgsmål, som må besvares af fremtidig forskning, herunder spørgsmål om omstillingen af tung transport og antagelsen om biomassens CO₂-neutralitet. Afhandlingen kan forhåbentlig bidrage til diskussionen om byernes energiomstilling, betydningen af forskellige former for energilagring, luftforurening i byer samt hvorledes modellering af energiomstillingen i byerne bør tilgås.

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1. Introduction

1.1. Background

Rapid urbanisation and swift technological changes are the two main driving forces behind the profound changes in urban energy systems. Currently, half of the global population lives in cities, producing 80% of the world's GDP, consuming 66% of the total primary energy supply and emitting 70% of the total energy-related CO₂ emissions [1]. By the year 2050, it is anticipated that the urban population share will rise to 66%, generating 85% of the world's GDP [1]. Gruber put the latter numbers into perspective by claiming that cities are part of ongoing exchange processes; they produce manufactured goods and services while they depend on a hinterland for their supplies, both energy and materials [2]. Densely populated cities, responsible for the majority of the primary energy consumption, economic activity and carbon-related emissions makes a case for focusing on urban energy supply in greater detail.

Technological changes impacting urban energy systems can be seen in a rapid decrease of the costs of distributed energy sources, such as photovoltaics (PV), wind turbines, solar thermal, energy storage and other renewable technologies. The costs of PV modules were 80% cheaper in 2017 than in 2010, while the wind turbine costs reduced by 50% over the same period [3].

Focusing on the specific energy sectors, 40% of global buildings energy use goes for space heating and cooling, while 40% of transport energy use occurs in cities [1]. As cities are more densely populated than the countryside, they are often suitable for district heating and cooling, different forms of public transport, as well as the development of more energy friendly transport options such as Mobility-as-a-service, biking, electrified trains, trams and subway. Moreover, cities offer opportunities for distributed PV, energy storage, electrification of heat and transport sectors, low-temperature district energy supply and integration of prosumers (both producers and consumers of energy) [1].

On the other hand, nowadays, densely populated cities often have problems with air pollution. Around 6.5 million deaths yearly are attributed to the air pollution, greater than the HIV/AIDS, tuberculosis and road fatalities combined [4]. The latter fact places air pollution at the 4th highest position on the list of the largest threats to human health [4]. The significant sources of air pollution are biomass for cooking, emissions from vehicles, industrial factories, power plants and other sources. Furthermore, International Energy Agency (IEA) states that the energy generation and utilization, mostly from poorly regulated or inefficient fuel combustion, are the most important man-made sources of air pollutants, responsible for 85% of particulate matter (PM) and almost all sulphur oxides (SO_x) and nitrogen oxides (NO_x) [4]. Thus, besides tackling gases that are exacerbating climate change effects (CO₂, N₂O and CH₄), urban energy modelling needs to take into account air pollution emissions, too.

This PhD thesis will aim for showing that the energy supply of future cities needs to be modelled taking into account wide range of interactions between different energy sectors (power, heat/cooling, mobility, gas and water) and also within the specific energy sectors. Moreover, it will be presented that successful integration of many different technologies will not be possible if energy supply modelling will be firmly separated from energy demand modelling; interactions between those two sectors need to be modelled combined to capture the real potential of flexible demand possibilities in energy sectors. Furthermore, the energy supply in future cities will be increasingly complex and a deeper understanding of the specific energy flows in the city will be needed in

order to find optimal or near-optimal energy solutions. Additionally, it will be shown that air pollution will also need to be accounted for when modelling energy supply of cities, as it can cause significant additional external costs to the society. Nevertheless, the difference between seeking for self-sustainable and integrated energy system with their surroundings of future cities will be presented regarding total socio-economic costs and differences in an energy portfolio. More specific novelties of the papers that form the core part of this PhD thesis can be found in *Novelties* section.

In order to make the findings of this thesis as relevant and as general as possible, three different energy models, one of which is developed in this PhD thesis, and six different energy systems as case studies are used. The case studies encompass different regions and sizes of energy systems, covering two different continents.

However, before proceeding with assumptions, methods, findings, conclusions and a future outlook, it is important to define specific terms that are important for this thesis.

1.2. Definitions

A model is a simplified representation of the real world that captures enough interactions to carry out technical analyses of different technical systems, as well as to infer about the future outcomes. Different models are used for different purposes, and it is important to retain enough interactions and complexity for a specific case being investigated. DeCarolís et al. claim that the problem should drive the analysis and not the vice versa, as well as that the analysis should be as simple as possible and as complex as necessary [5].

“Essentially, all models are wrong, but some are useful” (George Box, 1987)

An energy system is a system designed to extract, generate, convert and transfer different forms of energy to meet energy demand for different services. Its principal parts can be divided on energy supply, energy conversion and energy demand.

An urban energy system is an energy system located within the city boundaries, usually also exchanging the energy with the surrounding areas. In this thesis, the definition of boundaries of the urban energy system is taken from [6] for the so-called geographic-plus urban energy system definition: urban energy system consists of technologies that can be found within the administrative boundaries plus easily traceable upstream energy flows. The latter means that the PVs, solar thermal plants or wind farms that are not located precisely inside the administrative borders of the city can still be accounted for as energy supply of the city itself.

A smart energy system in this thesis is defined as combined and integrated electrical, heating, cooling, mobility, gas and water desalination sectors, with the aim of achieving additional efficiencies through potential synergies between different energy sectors and different storage types. It follows a notion that the optimal solution can be achieved when specific energy sectors are combined [7].

A district energy system encompasses both a district heating system and a district cooling system. It represents the overall system, consisting of supply, demand and distribution grid.

District energy supply is energy supply of district heating and/or district cooling systems.

Energy demand density in district heating and district cooling is defined as the demand for thermal energy per unit of land area (kWh/m²).

Variable renewable energy sources are renewable energy sources that are non-dispatchable due to its fluctuating origin. The examples include wind and PV technologies.

Temporal and spatial resolutions – represent the level of detail in covering geographical differences and potential for different sources such as wind and solar, as well as the level of detail of distribution grids (spatial resolution) and the level of detail in covering variations in energy demand in time. The finer the temporal and spatial resolutions are, the more complex the model becomes, sometimes resulting in an intractable model. On the other hand, coarser the spatial and temporal resolutions are, faster the computations are, but at the expense on the precision of the results.

Dispatchable energy sources, dominated in the incumbent energy systems, are usually easier for modelling as they can be dispatched as needed. On the other hand, variable renewable energy sources such as PV and wind cannot be dispatched at will, making it necessary to use finer temporal and spatial resolutions to capture their variability.

An urban heat island is an urban area that is warmer than the countryside due to the human-related activity. Examples can be exhaust from vehicles and heat rejected from different cooling devices.

Simulation is mimicking of the operation of a specific system in a real world. It is used to solve descriptive models, i.e. they seek to generate the development of the system over time, driven by the implemented simulation equations [8].

Optimisation is the selection of the best solution, based on the predefined criteria, among different alternatives. Contrary to simulation, optimisation follows prescriptive models, which generate a solution that best satisfies the selected decision criteria [8].

Air pollution is the occurrence of the elevated concentrations of harmful emissions for human health in the air. It includes gases, particulates and biological molecules. The most common air pollution-related emissions from energy systems and the ones that were modelled in this PhD thesis are SO_x, NO_x and particulate matter (PM) (both PM_{2.5} and PM₁₀).

Climate change is a change in climate patterns, mainly from the start of the first industrial revolution and caused by human-related activities.

Greenhouse gases (GHG) are the gases that contribute to the greenhouse effect by absorbing radiation in the infrared spectrum. They are dominated by CO₂ emissions, but also by CH₄ and N₂O and others. CO₂, CH₄ and N₂O were taken into account in this PhD thesis. When all CO₂, CH₄ and N₂O were taken into account, they were reported as CO₂e (carbon dioxide equivalent), meaning that CH₄ and N₂O emissions were recalculated as equivalent carbon dioxide emissions. More details about the exact method used can be found in Paper 9.

Carbon-neutrality, usually related to biomass, denotes no net release of CO₂ in the atmosphere. In relation to biomass, it follows from the assumption that CO₂ emitted while burning biomass was stored in the biomass during the growing phase. However, biomass is carbon neutral only if the additional amount of biomass compared to the last year is burnt, and if no negative land-use change effects took place.

An externality in economics is a consequence of certain actions which affects other parties without being reflected in market prices. Some examples are air pollution and climate change.

Non-point source pollution is pollution occurring from a vast area that is not easily attributable to a single source of pollution. Usually, its negative health effects are more serious than from point source pollution as they are more diffused across the atmosphere.

Point source pollution is a single source of pollution, which can be tracked and identified. An example is exhaust gases from a power plant.

Critical excess of electricity production (CEEP, or curtailed energy) – is the electricity generated in the power system for which there is no demand in that period. It is mostly caused by non-dispatchable energy generating more electricity than there is demand for. The CEEP can be exacerbated by non-flexible dispatchable power plants such as nuclear and coal-driven power plants. In the real world, electricity for which there is no demand needs to be curtailed as the electricity supply and demand need to match at every period.

Prosumers are producers and consumers of certain products. In energy terms, they represent consumers of energy that at specific periods feed the generated energy to the power grid or district heating or cooling distribution systems. An example is PV on rooftops that can at specific points of time feed the generated electricity to the grid.

Synthetic fuels are liquid fuels produced from syngas, using different chemical synthesis processes to obtain the wanted composition.

Syngas is a mixture of primarily hydrogen, carbon monoxide and other gases. In this PhD thesis, syngas was produced via solid-oxide electrolysis.

Electrofuels are synthetic fuels that used renewable electricity sources during all production stages.

An island mode in power systems represents the operation in isolation from the surrounding areas and their distribution networks.

A non-island mode in power systems represents the operation of the electricity system connected to the surrounding areas that allow for import/export of electricity over the city boundaries.

Self-sustainability is the attribute of the system that can maintain itself without the external interactions. In energy terms, it represents the energy system that can systematically meet all of its energy demand continuously without relying on the sources outside of the system boundaries. Self-sustainability also precludes the possibility of net calculation of renewable energy utilisation as it needs to continually meet all of its demands.

After defining the terms such as a model, an energy system and an urban energy system, one needs to distinguish between different energy models that are suitable for different (urban) energy systems.

1.3. Case studies used in the PhD thesis

In total, nine different case studies were used in scientific papers that form the present PhD thesis: the city of Sønderborg, the municipality of Sønderborg, the city of Zagreb, the city of Singapore (in this thesis Singapore was considered a city), the city of Espoo, different counties in Croatia, an island state of Aruba, the South-east Europe as a region, and the European Union.

The city of Sønderborg has a population of 27,500, and it is located in southern Denmark. More than half of the heat demand is covered by district heating. It has the largest district heating system in the municipality of

Sønderborg, with a total district heating production of 349 GWh in 2013. Its energy system in 2013 consisted of waste and gas cogeneration plants, gas and bio-oil boilers, geothermal energy coupled with biomass absorption heat pump and solar district heating plant. The share of residential demand in the total heat demand is 69%, higher than the average in Denmark, which is equal to 64%. The city of Sønderborg was used as a case study in Paper 7.

The municipality of Sønderborg has a population of 75,000 and an area of 496 km². The largest city in the municipality is the city of Sønderborg, and no other city has a population larger than 7,000. The total final energy consumption amounted to 2.1 TWh in 2013, with 500 kilotons of the associated CO₂ emissions. The municipality has five different (separated) district heating grids. Moreover, it is a net importer of electricity, as only 18% of electricity was generated within the borders in 2013. The energy generation system is dominated by waste cogeneration plant, gas cogeneration plants, gas and biomass boilers and lately solar district heating. The municipality is increasing its capacity in wind turbines and PV. The municipality of Sønderborg was used for a case study in Paper 3, Paper 6 and Paper 8.

Singapore is a city-state located in South-east Asia. It is dominated by hot and humid tropical climate, without distinct seasons. It has a population of 5.5 million, covering the land area of 719 km². The total primary energy supply was 325 TWh in 2014. The total final electricity demand was 49 TWh, and 95% of the generated electricity originated from the gas-driven power plants. Majority of the remaining electricity generation was met by waste incineration plants. It is importing all the gas needed for electricity generation. Singapore was used for a case study in Paper 5 and Paper 9.

Espoo is a city located in southern Finland, and it has a population of 270,000. Currently, its district heating generation is dominated by coal and natural gas cogeneration plants. The total district heating generation was 2,130 GWh in 2015. Furthermore, its district heating system has several installed boilers fuelled by natural gas, heavy fuel oil and light fuel oil. Moreover, they have one heat pump and one thermal energy storage. Espoo was used for one of the case studies in Paper 8.

Different counties in Croatia were used in one of the papers. Croatia has 20 counties and the capital city of Zagreb. The county with the smallest area is the city of Zagreb with an area of 641 km², while the county with the largest area is Lika-Senj, covering the area of 5,350 km². Population in different counties ranges from 790,000 to 51,000. In Croatia, the total primary energy demand was 97.7 TWh in 2015. The final electricity demand was 15.8 TWh in 2015, 37% being met by imports, 36% by hydropower, 13% by coal and 7% by natural gas. Only 1.4% of electricity was generated by biomass in 2015. Counties of Croatia were used for case studies in Paper 2. The city of Zagreb is the largest county in Croatia, with a population of 790,000 and currently, it is landfilling its waste, as it does not have a waste incineration plant. The city of Zagreb was used for one of the case studies in Paper 3.

Aruba is an island-state located in the Caribbean. It has a population of 104,000, covering an area of 179 km². The total primary energy demand was 4.96 TWh in 2012, almost entirely in the form of imported oil. Its final electricity demand was 0.88 TWh in 2012. Aruba meets all of its water demand by desalination, mostly via reverse osmosis technology, with an installed capacity of 47,000 m³ of desalinated water per day. The case study and the corresponding data used in Paper 10 were derived from measured data from Aruba.

The South-east European region was used as a case study in Paper 1. The region, as defined in the Paper 1, consisted of 11 countries. The largest electricity generation capacities in 2012 (the reference year) had thermal power plants with 37 GW, followed by hydropower plants with 23 GW, wind power with 4.6 GW, nuclear

power plants with 4 GW, PV with 2.2 GW and biomass power plants with 0.2 GW. The total primary energy demand was 1,400 TWh in 2012, while CO₂ emissions amounted to 321 Mt. South-east Europe as a region was used as case study in Paper 1.

The European Union was used as a case study in Paper 4, which focused on the transport sector. The EU includes 28 member states, has a population of 510 million and covers an area of more than 4.4 million km². The final energy consumption of the transport sector was slightly more than 4,000 TWh in 2013. Out of the total final transport energy demand, 82% was consumed by vehicles (out of which 59% was by light vehicles, 23% by medium and 18% by heavy vehicles), 14% by airplanes, and the rest by ships, rail and other transportation modes.

A large number of different case studies, regarding their energy generation portfolio, climate characteristics, size and the level of installed renewable energy sources, were used in order to make the results of the present PhD thesis more general, robust and easier to apply in different energy systems. This overview was intended to provide a general description of the case studies used, while more detailed descriptions of the corresponding case studies can be found in relevant papers that form this PhD thesis.

1.4. Novelties

As ten research papers form this thesis, there were also many novelties of those papers that are presented in this subchapter in a structured way.

In Paper 1, the whole South-east European region was modelled using the smart energy systems approach. It was shown that 100% renewable energy system is possible on a vast scale, keeping the biomass consumption sustainable. A further novelty of the paper was that the energy system was robust with no single energy source that contributed to primary energy supply with more than 30% of the total share. Moreover, it was shown that not only cross-sectoral integration is beneficial, but also regional integration can bring additional efficiencies to the energy system. Finally, it was shown how important energy efficiency is to energy transition in general, as it was shown that without energy efficiency measures taken into account, there would not be enough resources for the complete energy transition. This paper laid down the foundation for focusing on energy transition of smaller geographical areas, i.e. cities.

In Paper 2, the economic feasibility of biomass production was investigated, focusing on short rotation coppice production on unused agriculture land. The novelty was a quantitative estimation of the biomass production costs in different municipalities, its technical potential, obstacles and costs that would be used for running combined heating, power and cooling plant. Finally, the most influencing factors were presented in the sensitivity analysis.

In Paper 3, the issue of waste reduction for waste incineration plants, due to the more stringent recycling standards, was researched. The paper showed the interplay between the available waste for incineration and additional biomass that is needed to supplement waste. Moreover, an impact between different shares of waste and biomass incineration on the gate fees was investigated.

In Paper 4, a transition of the transport sector towards sustainable one was investigated. The novelty was a comprehensive bottom-up model that made it possible to quantitatively estimate the share of the transport sector that can be directly electrified with currently known technology. Moreover, another novelty was that it was explicitly calculated the amount of resources needed to make a complete energy transition of the transport

sector, including the part of the transport sector that cannot be directly electrified by the currently known technology.

In Paper 5, the main novelty was a coupling of the existing hourly input-output model with additional algorithms for the detailed operational planning of district cooling on a broad scale. Although district cooling was researched many times on smaller scales, this paper showed that it is possible for district cooling to be implemented in a systematic way city-wide and to serve as an integration point for variable renewable energy sources. Finally, it was shown that using excess heat from power plants and waste incineration plants for cold production via absorption chillers is socio-economically feasible on a large scale.

In Paper 6, the main novelty was the intra-sectoral integration of district heating systems, i.e. impacts of connecting adjacent district heating grids were investigated. The impact of integrated larger district heating grid on the energy supply was investigated in both current and future energy systems. Finally, the addition of waste heat from industry in the form of prosumers to the integrated district heating grid was assessed.

In Paper 7, the impact of the thermal building mass for thermal storage was researched on a system scale. The main novelty was that the impact of utilising thermal mass for storage was assessed on a district heating supply, contrary to the previous papers that focused only on the impacts on the power system supply. In order to carry out the research, a detailed building simulation model for different building archetypes was coupled with a system level energy optimisation model.

In Paper 8, the influence of different technologies on potentially dynamically priced district heating market was investigated based on two different case studies. A further novelty was that the impact of low marginal cost heat generation sources was assessed. Finally, the impact of storage on marginally priced district heating markets was calculated. A simulation model was developed to represent the day-ahead district heating market and to assess the impact of different technologies on the achieved marginal price of heat.

In Paper 9, energy model developed as a part of this study was upgraded to its latest, most integrated and sophisticated version. The final city-scale energy model included power, cooling, gas, mobility and water desalination sectors. It further included power-to-heat and power-to-gas-to-power technologies, flexible demand in industry and buildings, an endogenous decision on district cooling and individual cooling shares and an endogenous decision on energy efficiency scenario that is optimal to implement. Additionally, a significant novelty of this paper was that air pollution was modelled in an integrated way together with all the mentioned technologies and energy sectors. The case study was implemented on a city located in hot and humid climate, and the impact of stepwise integration of different energy sectors on the energy system supply was quantitatively shown. Finally, the difference between the self-sufficient island mode modelling and modelling of city integrated with its surroundings was presented.

Finally, in Paper 10, an integrated unit commitment operational planning (5-minutes resolution) was carried out, and the difference between operational planning (5-minutes) and energy planning (1-hour) regarding curtailed energy was presented. The main novelty was that it was shown that even the small island states could significantly improve the share of variable renewable energy supply at their portfolio, at a similar cost to the conventional island energy systems based on fossil fuels. Economically beneficial energy system could be simulated due to the usage of smart charging in the electrified part of the transport sector, flexible use of reverse osmosis for water desalination and ice (cold) storage implementation in hotels and resorts.

To sum up, the complexity of the topic and the broad scope of this thesis made it necessary to carry out several different research projects to tackle different specific topics of the urban energy supply. The remaining part of

the thesis presents different issues of energy supply of future cities, dominated by variable renewable energy supply, solutions and open questions in an integrated way in order to make it easier to follow for a wide range of the interested parties. It is important to note that the main novelties are discussed more thoroughly in the papers that form this PhD thesis, and further discussion that is presented in this thesis presents only the additional points that help to make the presentation of findings in an integrated way.

1.5. A review of the energy system models

The first broad review of the energy models was carried out in 2006 [9]. However, the latter review focused just on the general listing of the energy models available at that time, without more in-depth analysis and comparison of specific models. The first extensive review focused on the modelling tools that analyse the integration of renewable energy into various energy systems was done in 2010 [10]. In total, 37 tools were compared using a direct questionnaire. A review of urban energy system models carried out in 2012 reviewed 219 different papers using many different models [6]. DeCarolís et al. focused on energy economy optimisation models in their review carried out in 2012, considering 12 different energy economy optimisation models [11]. Another review of energy system models for energy challenges of the 21st century was carried out in 2014, reviewing ten other review papers which included 200 models and 748 publications in total [12]. In 2016, a review paper that focused on the UK case studies reviewed 110 papers with almost 100 different models [13]. DeCarolís et al. formalized the best practice for energy system optimization modelling in their review carried out in 2017, based on the collective modelling experience of the authors and extensive literature review [5], while another review paper carried out in the same year showed that majority of the models can be assigned to three different general methodologies [14]. Finally, a review carried out in 2018 focused on qualitative rather than a quantitative evaluation of energy system modelling frameworks, stating the main challenges and proposed solutions for them [15]. The overview of the relevant review papers of different energy system models and modelling tools can be seen in Table 1.

Table 1. Challenges, solutions and recommendations for different problems detected in the review papers of the energy system methodologies and models

Challenges	Solutions/recommendations/findings	Reference
<ul style="list-style-type: none"> The vast range of different modelling tools available Majority of tools have never simulated 100% renewable energy systems 	<ul style="list-style-type: none"> Selecting appropriate tools based on the specific use case EnergyPLAN, Mesap PlaNet, INFORSE and LEAP are the only tools that simulated 100% renewable energy systems accounting for all power, heat and transport sectors 	[10]
<ul style="list-style-type: none"> The complexity of the modelling domain Data availability and quality Policy relevance Model integration within the modelling community of the urban energy systems 	<ul style="list-style-type: none"> Sensitivity analysis for uncertainty reduction and cloud computing for better data handling Data collection unique standards Model integration via activity-based modelling 	[6]
<ul style="list-style-type: none"> Inability to verify models' results due to hidden flows in the source code, value-based assumptions driving the results, highly sensitive parameters obscured 	<ul style="list-style-type: none"> Keeping models publicly available, including the source code and detailed documentation Making model data easily available Making transparency a target 	[11]

<ul style="list-style-type: none"> and not published in the available analysis Data collection Model validation 	<ul style="list-style-type: none"> Using free software tools Developing test systems for verification purposes Seeking towards interoperability between different models 	
<ul style="list-style-type: none"> Resolving temporal and spatial details in optimisation models Uncertainty and transparency of simulation models Appropriately addressing increasing complexities in the power systems models Integrating human behaviour modelling into the qualitative models 	<ul style="list-style-type: none"> Using real-time series Reducing the model complexity to be able to carry out rigorous sensitivity analyses Using simplified heuristics and integrating different models Developing actor based scenarios, developing a wide range of cost-effective model-based scenarios, using multi-objective optimisation 	[12]
<ul style="list-style-type: none"> A side-by-side comparison of models is constrained by lack of clarity of model characteristics and underlying working mechanisms The most prevalent model is MARKAL (general equilibrium energy economy optimisation model) 	<ul style="list-style-type: none"> Only a review has been carried out, without clearly stated proposed solutions 	[13]
<ul style="list-style-type: none"> Taking into account the complexity of the energy systems, modellers need to carry out a significant amount of judgement that can make modelling a blend of art and science A wide range of different methodological approaches and models is available in the literature 	<ul style="list-style-type: none"> Carrying out an analysis based on the problem and not the vice versa Making analysis as simple as possible and only complex as needed Taking care of data quality assurance Making sectoral details based on the problem being analysed Checking targets and hypothesis throughout the analysis Dealing with uncertainties in both endogenous and exogenous data Taking care of transparency as a target of the analysis itself 	[5]
<ul style="list-style-type: none"> Temporal and spatial level of details Technical representation of the system 	<ul style="list-style-type: none"> Soft linking integrated assessment models that have a good long-term general representation of the energy system with an operational power system models that have a sufficient level of spatial, technological and temporal details 	[14]
<ul style="list-style-type: none"> Scientific standards The complexity of the energy systems Interdisciplinary modelling Uncertainty in data and results Usability and reusability of models 	<ul style="list-style-type: none"> Using open-source software and making the code publicly available Collaborative development among modellers using consistent terminology for adequately addressing interdisciplinary Modular framework with object-oriented implementation to make the models more flexible 	[15]

One can note from the review presented in this section that a wide range of models and modelling tools for energy systems exists. Generally, it can be noted that several review papers claimed that an appropriate model should be chosen based on the specific case being modelled. Furthermore, newer review papers emphasised the need for transparency of data used in the model, source code as well as the model documentation.

1.5.1. Bottom-up versus top-down modelling

There are two general approaches when modelling energy systems, bottom-up and top-down ones. A bottom-up approach includes a detailed representation of technologies with both technical and economic characteristics. It is more focused on the technologies itself and less with its impact on the overall economy [16]. The bottom-up approach is mostly used to calculate the least-cost solutions, subject to different constraints [17].

A top-down model is focused more on general interactions between the economy and energy sectors. It lacks detailed technological representations as it is the case with the bottom-up models. Top-down models capture market processes in an aggregated manner, based on historical data [17]. Due to the aggregated modelling, the top-down model is not suitable for evaluating specific policies and impacts of specific technologies.

Traditionally, bottom-up models have ignored consumer preferences and potential hidden costs, while they have focused on technology-related and energy-related issues. On the other hand, top-down models often over-estimated the future investment costs of renewable technologies due to its focus on historical data [13]. However, the spasm between top-down and bottom-up models' results has decreased according to the Fourth Assessment Report from the Intergovernmental Panel on Climate Change [18].

The present PhD thesis focused on technological issues of the energy system transition and hence, bottom-up energy system models were used to represent interactions between different energy systems in great detail. As the focus of the PhD thesis was on the supply side of the energy system, it lacks the inclusion of human behaviour modelling which could influence the obtained results.

1.5.2. A review of the models used in this PhD thesis

Three different energy system models were used in the present PhD thesis in order to successfully model a wide range of case studies and to generalise the findings of the thesis. The models used were EnergyPLAN, Plexos and a self-developed linear optimisation model.

EnergyPLAN is simulation software based on the deterministic input-output model [19]. It has been developed by Aalborg University, and it is used for energy system analysis, feasibility studies and public regulation [20]. The tool is based on the concept of smart energy systems in which electricity, heat and mobility sectors are taken into account holistically with modelled interactions between those sectors [20]. In the scientific literature so far, the EnergyPLAN modelling tool was mainly used for the integration of renewable energy sources into energy systems [21]. Moreover, the EnergyPLAN was mostly used for national and regional case studies [21], while its main analysis criteria were primary energy supply, CO₂ emissions, CEEP and system costs [21]. The EnergyPLAN modelling tool is freeware, although the source code is not available to users. Detailed documentation is available for download [19]. In the present PhD thesis, the EnergyPLAN modelling tool was used in Paper 1, Paper 3, Paper 4 and Paper 5.

The linear optimisation model, developed as a part of this thesis, had the objective function set to minimise the total socio-economic costs of the energy system. It had an hourly time resolution, with one full year taken into account. It was used in different varieties in Paper 6, Paper 7, and Paper 9. It was initially developed in Paper 6, where it was used for modelling of integration of adjacent district heating systems. In Paper 7, the optimisation model was soft-linked with a detailed dynamic building level simulation model. In Paper 9, the previously continuous linear optimisation model was updated to mixed-integer linear optimisation model to allow for endogenous choice of energy efficiency scenarios. Moreover, the most updated version of the model was used in Paper 9 and thus, readers are encouraged to check the Appendix B of the Paper 9 in order to check the modelled interactions. The final version of the optimisation model included power, cooling/heating, mobility, gas and water desalination sectors, with many modelled technologies. The most updated version of the model endogenously chooses the optimal share between energy supply, energy efficiency measures and the level of district energy supply. It has five different energy storage types modelled, i.e. batteries of vehicles, grid batteries, methane storage, hydrogen storage and thermal energy storage. It has further modelled power-to-heat and power-to-gas-to-power technologies, as well as integrated reverse osmosis (RO) technology for water desalination into the modelled energy system. Finally, the model endogenously chooses the optimal level of demand response in industry and households. The model can operate in both island and non-island mode. A scheme of the final version of the optimization model can be seen in Figure 1. The optimisation model was developed using Matlab interface and Gurobi solver. The student's Matlab license can be obtained for 279 DKK + VAT in Denmark, while the Gurobi solver is free of charge for academic purposes. The source code is freely available to potential users.

Contrary to EnergyPLAN, the developed optimisation model was used for smaller geographical areas, i.e. cities, which are dominated by more interactions and technological diversity than the national and above-national modelling. Moreover, by developing the optimisation model, the optimal investment portfolio could be chosen by the model, reducing the amount of time a modeller needs to spend to find the optimal technology portfolio for energy systems of cities. Finally, using optimisation instead of simulation software allowed for detailed optimisation of different storage solutions, as the examination of the operational behaviour of different storage types was an important part of this thesis.

Plexos software is an integrated energy model that uses mathematical optimisation to simulate the detailed operation of the integrated power, gas and water systems [22]. It is a flexible modelling tool that allows different spatial and temporal resolutions. It can use deterministic and stochastic optimisation to simulate the operation of the energy system, while the objective function is to minimise the total operational costs of the energy system [22]. The Plexos software is mostly focused on the power sector, and its features are modelled in great detail [23]. The Plexos software solves a unit commitment problem when simulating the operation of the energy system, taking into account detailed constraints for system operation, ancillary services and maintenance. It has a user-friendly interface. The Plexos license is commercial, the source code is not available to its users, and the detailed documentation is available, as well as user support after the license has been obtained. The license can be provided free of charge for academic and research purposes.

The Plexos software was used in Paper 10 for modelling of an island energy system with an emphasis put on the detailed operational simulation of the system, focusing on the integration of considerable share of variable renewable energy sources.

In remaining papers that are an integral part of this PhD thesis, smaller and very case-specific models were developed to examine very detailed technologies and their role in energy systems.

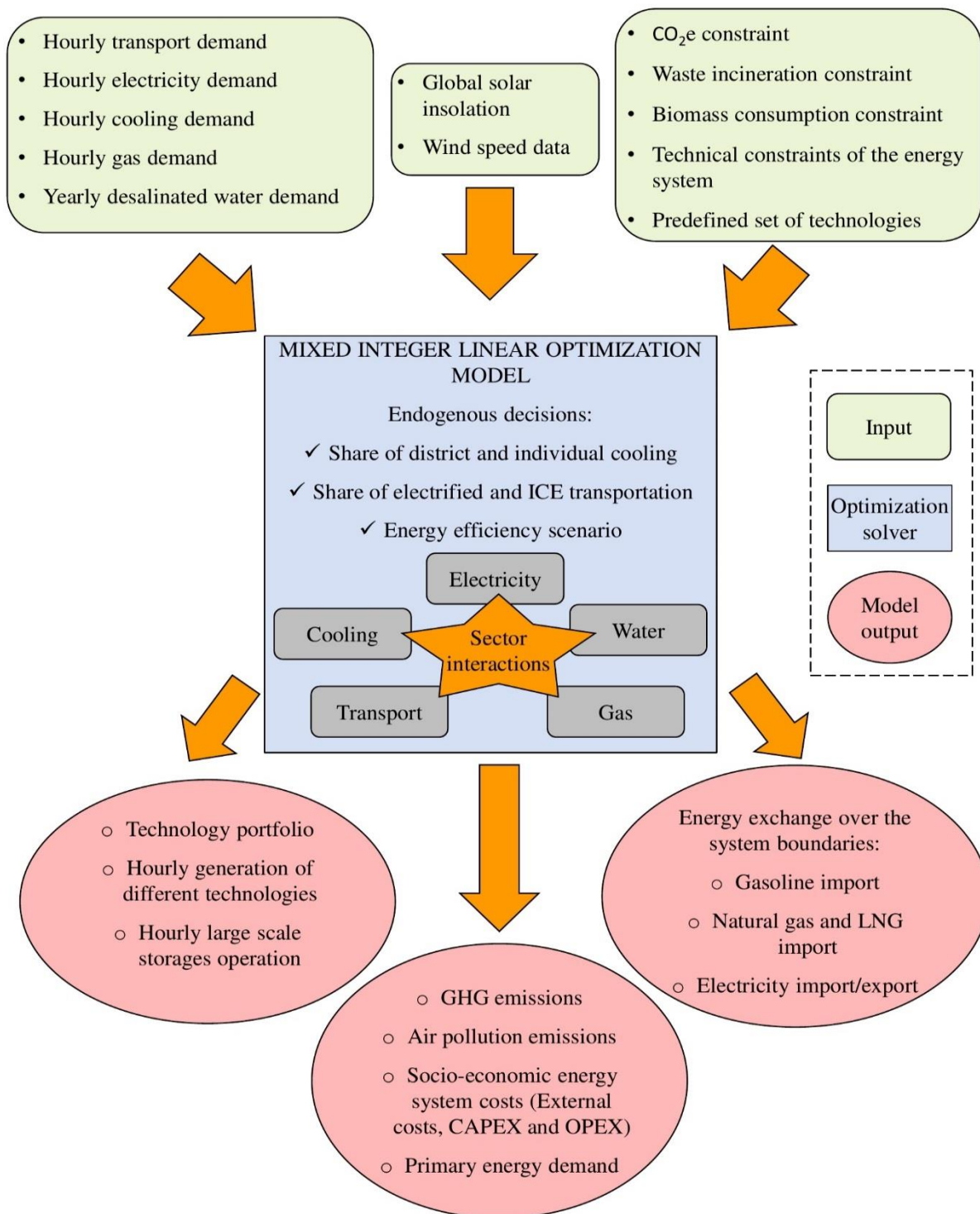


Figure 1. A scheme of the most updated version of the integrated optimization model for urban energy systems developed in the present PhD thesis [Paper 9]

1.5.3. Energy modelling and planning in city perspective: sustainable development and interdisciplinarity of research

“Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [24] is one of the most famous definitions of the sustainable development. Sustainable development consists of economic, environmental and social pillars and they cannot be examined in isolation of each other. Hence, managing interdisciplinarity in energy (environmental) modelling is an important task that makes the process of energy planning increasingly complex.

Many material and energy flows can be taken into account when modelling urban energy systems. If one takes into account the life-cycle assessment, material for insulation of buildings, land use change and externalities of carbon emissions, models can rapidly become computationally intractable. Moreover, if done correctly, integrated urban planning needs to be founded on interdisciplinary collaboration [25]. Furthermore, the current literature has challenged the notion that solutions found in one city can be transferred to another city without imposing a risk of serious negative feedbacks [25].

Especially important can be the influence of decentralised energy generation and the rise of the so-called prosumers, consumers that also produce energy at certain times. The latter can influence the acceptance of new technologies, improve the financing possibilities of energy transition and turn the passive consumers into active participants of energy transition, also helping to curtail unsustainable patterns of energy consumption [26].

A possible methodology for the planning of sustainable transition in cities in an interdisciplinary way was presented in [27]. The authors used experts from different areas in operating teams, used the on-site gathering of information in a city and used a triple helix approach with representatives of academia, industry and municipality jointly collaborating on finding the solutions. Although many different solutions were proposed, only conceptual results were presented, and no real implementation has been proposed. The triple helix model can be expanded in a quadruple helix model where civil society is also added to the planning team of an urban transition [28]. In theory, the involvement of many different stakeholders should improve the solution and remove the feeling of certain parties that they are being left out of the decision-making process [28].

From the review of the available modelling tools, as well as from the overview of many involved stakeholders in urban energy transitions, one can get a grasp of the complexity of the transition process itself. In this PhD thesis, representatives of different universities, institutes and industry were collaborating on the solutions for energy transition that were presented in the scientific papers attached to this thesis. Hence, a potential limitation of this study is that it did not directly involve civil society and governmental representatives in the modelling. The solutions presented here are more technically inclined, and proper policies for implementing the results obtained in the present PhD thesis should thus be considered with governmental and civil society representatives, too.

1.5.4. Energy sectors in cities and accounting methods

Similar to any size of the energy system, the primary goal of urban energy systems is to meet the service demand for energy. However, urban energy systems have some specifics compared to the national energy

systems; they have high population density, due to which air pollution has more significant impact, and they have a high concentration of human capital that makes it easier to innovate and carry out a transition to a more sustainable form of energy system [2].

Although traditionally energy was centrally produced and supplied towards the city, a rise of distributed energy sources such as PV, micro CHP systems, solar thermal, heat pumps and others are changing that paradigm. Furthermore, a wide variety of storage solutions can make them both central and decentral solutions. Traditionally, a potential energy source that cities need to take care of is waste [2], while they most often have some potential for biomass utilisation, besides the solar potential that exists in any region. Moreover, the water sector, together with electricity, thermal, gas, and mobility sectors cannot be distinguished when looking into urban energy systems and its resources.

Finally, in order to carry out energy modelling of cities, accounting methods need to be set before the modelling can be carried out, and results can be discussed. One can have different accounting methods for energy consumption, depending on whether it includes the embedded energy in products consumed inside the city. Similarly, CO₂ emissions can be accounted for using only directly emitted CO₂ emissions within city boundaries, or including the embedded emissions during the production phase of products used inside a city. Finally, biomass CO₂ emissions can differ based on the accounting method used and whether the life cycle analysis has been taken into account, including the potential land-use change.

Most of the papers that form this PhD thesis focused on different issues that occur in urban energy systems, taking into account electricity, heating/cooling, gas, mobility, and water desalination sectors. In Paper 2 and Paper 3, an emphasis was put on the waste management, a combination of waste and biomass utilisation for different recycling targets, as well as potential for increasing the sustainable biomass supply. In Paper 4 an emphasis was put on the mobility sector. In Paper 5, Paper 6, Paper 7 and Paper 8, district cooling/heating energy systems were in focus, although always in the holistic energy system perspective. In Paper 9, all the above-mentioned energy sectors were holistically modelled, including the demand flexibility options. Finally, Paper 10 included integrated operational planning of power, cooling, mobility and water desalination sectors for an island-country.

Only direct energy and CO₂ emissions were accounted for in the research papers, due to the lack of the available data for a more detailed accounting from a demand perspective, which would include embedded energy and carbon emissions. Biomass was modelled as a carbon neutral source, although it was taken into account that only the amount of biomass that was increased compared to the previous year can be utilized sustainably, in order to maintain the carbon neutrality of it. If there would be no biomass that could be utilized within the system boundary, as it was the case in Paper 9, biomass had to be produced within the system. For the case of Singapore in Paper 9, that was done via algae production.

Although already many sectors were considered in this PhD thesis, one can note that even more sectors could be included in integrated energy planning. Those could be water distribution systems that demand a certain pumping power, as well as storm-water and waste-water systems with the potential for utilisation of their low-temperature heating sources for district energy systems. Finally, looking at the demand side, an industry sector was not modelled in great detail in case studies due to the lack of available data of its industrial and energy conversion processes. Hence, the mentioned simplifications could have impacted the results obtained in this PhD thesis.

2. General discussion in the context of the enclosed papers

2.1. The role of biomass in future cities and its impact on air pollution

The role of biomass was one of the most important aspects of this thesis. The biomass role was examined in Paper 1, Paper 2, Paper 3, Paper 4, Paper 6, Paper 7, Paper 8 and Paper 9. Biomass is an important source for the energy transition as it is considered to be renewable and carbon neutral (e.g. the European Commission and the US Environmental Protection Agency adopted a carbon-neutrality approach). Carbon neutrality stems from the notion that the released CO₂ when the biomass is being combusted was stored in the same biomass during its growth phase. If the incinerated biomass does not decrease the overall amount of living biomass compared to the previous year, no additional carbon emissions occur at the overall scale. Furthermore, biomass can be used as a fuel for power plants (PPs), combined heat and power plants (CHPs), heat only boilers, but also for transport sector for the biofuel production. Moreover, both biomass driven PPs and CHPs are dispatchable, and thus, they can provide a certain level of security in energy supply. In the transport sector, biofuels can be blended to the traditional diesel and gasoline fuels without problems caused for existing engines. Biodiesel can be directly injected into the vehicles using petroleum-derived diesel, without any engine modifications needed [29]. Furthermore, ethanol can be injected into traditional gasoline engines, and currently, most of the countries inject a certain amount of ethanol into the gasoline. Brazil has been a forerunner in the ethanol usage, and since 2003, single engine hardware with corresponding software controls in Brazilian vehicles can automatically adjust to different blends of ethanol and petroleum-derived gasoline, up to the 100% of ethanol fuel [30].

In addition, there are many competing uses of biomass in energy systems, such as in power, heating and mobility sectors. Hence, the optimal or near-optimal biomass mix in each sector needs to be sought for, in order not to make biomass consumption unsustainable.

In Paper 1, the overall biomass consumption was one of the constraints of the energy system. The resulting system consumed just under the total sustainable biomass potential of the region, which was 28.7% of the total primary energy supply. However, a sensitivity analysis showed that biomass consumption could become unsustainable in dry years. An energy mix of the energy system for the year 2050, a scenario that had zero carbon emissions, showed that 9.2% of the total biomass consumption occurred in the industry sector, 6.6% in buildings, 27.4% in transport and 56.8% in power and district heating sectors. Finally, it is important to mention that a significant part of the transport sector underwent transition towards electrofuels (synthetic fuels) in order to keep the biomass consumption sustainable.

In Paper 2, it was investigated whether the sustainable biomass potential could be increased by utilising short rotation coppice on unused land. Several different case studies were carried out for several different counties in Croatia. The results showed that the biomass price from short rotation coppice production would be significantly higher than the price of currently available biomass. Although the potential amount of biomass that could be produced for chosen case studies was large, due to a large amount of unused agriculture land, a net present value (NPV) of a potential CHP plant was negative even at optimal locations of the plant. The potential biomass increase due to the cultivation of it on unused land was calculated to be 1.61 TWh/year in the six best performing counties (out of 21 in total), which equals to 10.3% of the current sustainable biomass potential in Croatia.

Paper 3 dealt with the problem of the lack of waste after the stricter recycling targets are imposed. The most common approach to keep the waste incineration plants still economically feasible is to add a certain share of biomass into the incinerator. A comparative case study was carried out, one for the case of Zagreb and one for the case of Sønderborg. In the years with the most considerable demand for additional biomass to be burnt in waste incinerators, 56.3% of the total fuel heating value originated from biomass in the case of Zagreb and 41.1% of the total fuel heating value originated from biomass in the case of Sønderborg. The latter number shows how cities could face a significant additional demand for biomass in the future if they continue to pursue stricter and stricter recycling standards.

Paper 4 dealt with the problem of energy transition in the transport sector and its impact on the overall energy system. Although the paper followed the approach that everything that can be directly electrified should undergo electrification, still only 72.3% of the transport sector could be directly electrified. The remaining share needs to be subjected to other alternative solutions, and one of those solutions is to replace that fossil fuel demand with biofuel demand. However, on the EU level, the calculated biomass needed in the case of biofuels utilisation scenario was 3,070 TWh of additional biomass, which is more than the total biomass potential assessment for the year 2050, even if the whole sustainable biomass would be directed towards the transport sector. The latter number should make us wary of the non-critical use of biomass in the transport sector, and it further calls for alternative solutions in the transport sector. Hence, related to findings in Paper 4 of this thesis, city energy planners should seek for electrifying as much of the transport sector in cities as possible, as well as using other alternatives for heavier transport than the biofuels, as the sustainable part of biofuels will most probably be needed in the aviation sector.

Paper 6 dealt with the possible integration of adjacent district heating systems. A case study was carried out for the case of the municipality of Sønderborg. As some of the district heating systems had biomass driven boilers and some did not, it was possible to follow the biomass consumption before and after the grid interconnections. The results showed that the biomass demand would increase at the expense of the gas and electric boilers production (Cases I to V). However, in cases VI to IX of the Paper 6, one can notice that the biomass demand can be decreased if the waste heat and centralised heat pumps are introduced into the district heating grid. Hence, in the future development of district heating in cities, energy planners need to take into account that feeding waste heat from prosumers into the district heating grid can save a certain amount of biomass for other purposes. Contrary to the latter, one must be aware that although beneficial from the socio-economic point of view, replacing gas consumption with biomass driven heating and power plants can significantly increase biomass demand. In cases I to V of the Paper 6, the increase in biomass demand in district heating systems was equal to 49%.

Paper 7 dealt with the potential utilisation of thermal mass of buildings for storage and its potential impact on district heating energy supply. The case study was carried out for the case of the city of Sønderborg and the results presented in Table 8 of the Paper 7 show that the thermal mass utilisation can improve the effective generation of variable renewable energy sources, i.e. solar district heating in this case, reducing the biomass consumption in the same time. Biomass consumption was most significantly reduced for the scenario that was carried out for the year 2029, when more thermal mass utilisation could be expected, due to the better insulated buildings in general. Hence, one can conclude from this paper that the implementation of thermal mass for storage in district heating systems can help reducing biomass consumption, saving it for other energy purposes.

Paper 8 dealt with the potential consequences of dynamically priced district heating markets, similarly to the way electricity day-ahead markets operate today. The results showed that if the heat generation plants were

marginally priced in the energy system, the addition of waste heat, waste heat coupled with the additional amount of solar district heating and waste heat coupled with both solar district heating and heat pumps would all reduce the amount of biomass consumption in the energy system. All other capacities equal, an addition of seasonal thermal energy storage would cause a slight increase in biomass consumption as it would replace a part of the gas consumption.

Paper 9 dealt with a holistic energy modelling of a city located in hot and humid climate. Biomass issue can be examined here both via the energy analysis and via air pollution analysis. One should note here that as the chosen case study was the city of Singapore, which does not have any significant sustainable amount of biomass, all the sustainable biomass needed to be produced, in this case from sea algae. In the Scenario 6 of the Paper 9, the one that had strictly constrained allowed CO_{2e} emissions, one can notice a sudden and significant increase in biomass consumption. In the Scenario 6, biomass had a share of 42% of the total primary energy consumption. As a consequence, air pollution levels significantly increased. Particulate matter (PM) emissions and SO_x emissions were significantly higher than in any other scenario, i.e. PM emissions were 7.4 times higher than in the Business-as-usual (BAU) scenario, while SO_x emissions were 75 times higher than in the BAU scenario. NO_x emissions were 25% lower than in the BAU scenario but still higher than in any other alternative scenario. Furthermore, when the same strict CO_{2e} emissions constraint was imposed in the energy system, but when the system did not need to be self-sustainable, i.e. it could have utilized the energy sources from its surroundings, biomass consumption and the corresponding air pollution significantly dropped, as can be seen from the Scenario 7 of the paper. In the Scenario 7, PM emissions were 6.5 times lower, SO_x emissions were 6.6 times lower, and NO_x emissions were 5.7 times lower than in the Scenario 6, for the same amount of emitted CO_{2e}.

General conclusion and recommendations: One can already grasp how vital is the role of biomass in energy supply of future cities. Sustainable biomass is an extremely scarce resource and should be utilized sparingly in order to make it possible to carry out a transition of the whole energy system, including the transport sector. Paper 1 and Paper 4, which focused on the modelling of the larger geographical scale, showed that even biomass-rich regions would have problems utilising it sustainably. The transport sector is especially troublesome, and it was shown that even with significant electrification of the transport sector there is still not enough biomass for the heavy vehicles, long-haul transport and airline transportation and thus, different alternatives need to be sought for. Biomass will need to be shared between industry, buildings, energy and transport sectors and it is important not to rely too heavily on biomass if one models only one of the mentioned sectors. It is vital to maintain the biomass consumption sustainably across a wide range of sectors.

Results of the papers showed that a particular share of biomass would need to supplement waste incineration upon the implementation of the more stringent recycling standards. Second, sustainable biomass potential could be technically increased via utilisation of the unused agriculture land, but this option is still not economically feasible. Third, biomass demand in the sustainable energy sector could be reduced by integrating waste heat and centralised heat pumps into district heating, utilisation of thermal mass for storage and an additional amount of solar district heating coupled with large-scale thermal energy storage. The biomass demand could be further decreased by utilising the other energy resources available in the cities' surroundings, contrary to focusing solely on the energy resources available strictly within the boundaries of the cities. On the other hand, biomass consumption increased at the expense of gas and electric boilers when the current socio-economic set-up of the energy systems was simulated.

Nevertheless, it is essential to take into account the potential air pollution in cities that can be caused by excess biomass utilisation, as was shown in the Paper 9. The same paper further showed that the non-point source

PM emissions are much dearer regarding external costs compared to the point-source PM emissions. Hence, in the future, the inevitable use of biomass will need to be carefully assessed versus the potential air pollution emissions.

Comparison with other available literature

Biomass is often a predominant choice when modelling sustainable energy supply of the future energy systems. For example, the modellers showed that due to the taxation, wood pellets are overwhelming energy source from private-economic perspective, as shown in the case of Helsingør [31]. However, from socio-economic perspective, district heating systems are the optimal solution, in line with the findings of this PhD thesis. Moreover, in [32], the authors have shown that the district heating solution would be the optimal solution if socio-economic calculation would be used, also reducing the air pollution externalities [32], the result that is in line with the findings of this thesis. However, based on the private-economic calculation presented in their research paper, the citizens decided to opt for either biomass boiler or heat pump [32].

Another study focused on the air pollution modelling if wood pellets boilers would replace electric heating [33]. The results have shown that the wood pellets would not significantly increase air pollution levels, although district heating solution proved to be even less air polluting [33]. The latter finding is in collusion with the Paper 9 of this thesis which found that biomass can significantly increase air pollution levels. It is also in collusion with the IEA report [4] which stated that biomass is a significant source of the NO_x, SO_x and PM emissions in cities and another research paper [34] which showed that biomass is one of the primary sources of PM emissions, along with the traffic and industrial activities.

Future research

For the future research, two central questions need to be thoroughly addressed in order to assess the real potential of the biomass in future energy systems. First, it will be needed to clarify the assumption of the carbon neutrality from the life-cycle perspective. Second, a deeper understanding of the connections between the air pollution in cities and biomass use, especially as non-point source pollutant in the form of the biofuels used in vehicles, will need to be established.

Concerning the carbon neutrality assumption, recently it was argued that the biofuel sustainability is a complicated question without a clear answer [35]. It was further argued that due to the low energy density, food production should be given priority over energy production in the urban agriculture sector [35]. The carbon neutrality of biomass was even more challenged in a recent letter [36]. The authors stated that the carbon payback time is in the range of 44 to 104 years, given that the land remains forest. Moreover, the authors of the letter raised the concern that as the electrical efficiencies of biomass burning compared to the coal burning are much lower, the immediate impact of coal replacement by biomass is an increase in the carbon emitted. Finally, the author in [37] heavily criticised the assumption of the carbon neutrality of biomass, and even more so of biofuels, and claimed that the crucial variable in estimating carbon neutrality of biomass is the potential land use change. Thus, more research on this topic will be needed in the future.

2.2. Roles of different flexibility options in energy supply of cities

2.2.1. Energy storage

Energy storage was another significant aspect that was addressed in this thesis. In total, five different storage types were assessed as a part of this thesis. Those were grid battery storage, battery storage in vehicles (electric vehicles), natural gas (methane) storage, hydrogen (syngas) storage and thermal energy storage. This topic was tackled in Paper 1, Paper 5, Paper 6, Paper 7, Paper 8, Paper 9 and Paper 10.

In Paper 1, natural gas, thermal storage and pumped hydro storage types were implemented. In total, 78 GWh of gas storage (both methane and hydrogen), 230 GWh of thermal energy storage and 1067 GWh of pumped hydro storage capacity was installed. To put the latter number in relation, the peak district heating demand was 38 GW, and the average district heating demand was 13 GW. The peak electricity demand was 45 GW, and the average demand was 35 GW. The maximum demand for methane was 2 GW and for syngas was 8 GW.

In Paper 5, ice (cold) storage was implemented within the system in order to provide the flexibility to the energy system with a high share of variable renewable energy sources. The total capacity of the ice storage was 7.7 GWh_c, which would equate to a volume of 90,500 m³. For comparison, the peak district cooling demand was 3.5 GW_c.

In Paper 6, the total of 2.3 GWh of pit thermal energy storage was installed in the case study carried out for the year 2029. For comparison purposes, the peak district heating demand for the case study for the year 2029 was 104 MW.

In Paper 7, two distinct storage types were installed. One was the pit thermal energy storage, and the second one was a thermal mass of buildings which was used as short-term storage. The installed capacity of the pit thermal energy storage was 4 GWh, while the total utilized thermal mass for storage was different according to the specific case study. In the case with two hours of preheating of thermal mass, which was carried out for the year 2029, the maximum utilized capacity in a single hour was 37 MW. By utilizing the thermal mass for storage in the latter scenario, a total of 33 GWh of district heating demand was shifted to the later periods. An important finding was reached in the sensitivity analysis that was carried out; the large-scale pit thermal energy storage and the thermal mass for storage proved to be complementary in the energy system.

In Paper 8, the total installed capacity of pit thermal energy storage was 750 MWh for the case of Sønderborg and 800 MWh for the case of Espoo. The paper simulated the potential behaviour of the thermal energy storage on the dynamically priced district heating market and examined its impact on the prices and revenues in the market. For the case of Sønderborg, the storage decreased the marginal heat prices and the total yearly turnover when it was installed in the currently operating setup. The decrease in the weighted average marginal price was 3.1%. For the case when thermal energy storage was added along with the waste heat from industry, more solar district heating and heat pumps, the weighted average marginal price increased for 0.3% as more nearly zero marginal cost heat was utilized. For the case of Espoo, the inclusion of storage decreased weighted average marginal prices, for 0.5% compared to the reference scenario and for 0.8% when also geothermal energy and waste heat from data centres were utilized.

In Paper 9, the role of storage was very significant as five different storage types were modelled and their behaviour examined. The installed capacities of different storage types were different in specific scenarios, as it can be seen from the Table 9 of the Paper 9. In the Scenario 7 of the paper, that was the most constrained one in terms of allowed CO_{2e} emissions, the total installed capacity of a pit thermal energy storage was 492 GWh, grid battery storage was 21 GWh, hydrogen (syngas) storage was 223 GWh, natural gas storage was zero and batteries in electric vehicles was 23 GWh. Looking at all the scenarios, the pit thermal energy storage was the one with the largest capacity installed. In Appendix A of the Paper 9, one can find detailed figures presenting hourly behaviour of every storage type throughout the year. It can be seen from those representations that none of the storage types had a constant intra-day pattern of charge and discharge. That leads to the conclusion that storage solutions cannot be optimally represented if different time-slicing and typical days approaches are used, as those approaches can only capture intra-day storage behaviour. Moreover, this paper showed that optimal capacities of different storage types, when using integrated energy modelling approach, heavily incline towards thermal energy storage in comparison with the battery storage solutions. One should note here that no upper bounds in terms of installed capacity were set on either of the storage types.

In Paper 10, the ice (cold) storage was used in hotels and resorts in order to make energy system more flexible and to allow for large penetration shares of variable renewable energy sources. The total installed capacity of the ice storage was 820 MWh, which was equivalent to the 3 days of average cooling energy demand. By implementing the ice storage solution, along with the smart charging of electric vehicles and flexibly utilizing an excess capacity for reverse osmosis, it was possible to meet 78.1% of the total electricity demand with variable renewable energy sources (one should also note that for the chosen case study wind and PV load factors were very beneficial, i.e. they were 54.1% and 25.3%, respectively, without present seasonality in PV generation).

General conclusion and recommendations: As the role of different storage solutions was very often included in research papers that are part of this thesis, several general conclusions can be made. First, integrated energy modelling is essential to capture the optimal behaviour and capacities of different storage solutions, as it was shown that different storage types do not follow regular daily patterns of charging and discharging. Second, during the modelling phase of several different papers of this PhD thesis, it has been shown that the optimal capacity of thermal energy storage is significantly higher than the capacity of battery storage. The reason for the latter behaviour was mainly the much lower installation cost of the thermal energy storage compared to the battery storage, even if the medium term price drop expectations for batteries are taken into account. Third, in district heating systems, both large-scale thermal energy storage (pit thermal energy storage) and short-term storage (thermal building mass for storage) can serve complementary roles, increasing the flexibility of the system in the same time. Fourth, focusing on the power storage solutions, if the region is suitable for pumped hydro, its optimal installed capacity can be substantial, which was shown in the Paper 1. However, more often is the case that the optimal capacity of the thermal energy storage will be significant in comparison with the electricity storage.

Hence, energy planners and modellers of energy supply in future cities should focus on integrated energy modelling when looking for optimal storage capacities in order to capture the usually optimal set-up that includes large capacities of thermal energy storage. Moreover, they should be careful in reaching conclusions about the optimal storage capacities if they use different time-slicing approaches, as different storage solutions do not necessarily follow regular diurnal charging patterns.

Comparison with other available literature

In [38], it was claimed that the thermal energy storage is much more economically sensible compared to the electricity storage due to the significantly lower investment costs. Moreover, it was claimed that the nature of variable renewable energy production dictates the need for storage to have a low number of the full load hours, with long storage periods [38]. The latter finding is in line with the findings of this study, especially with Paper 9 from this thesis. In the latter paper, it was shown that capacities of thermal energy storage are much larger than grid battery storage. Furthermore, in Appendix A of the paper, it was shown that the thermal energy storage behaves closer to the long-term than to intraday storage, confirming the hypothesis from the [38] about the storage behaviour in the energy systems with a significant amount of variable renewable energy sources.

Similarly, in [39], the authors claimed that thermal storage and especially gas and liquid storage are feasible for storing energy with a relatively low number of full annual cycles. This thesis confirmed the latter stance, as both methane and hydrogen storage, as well as the thermal energy storage, had much larger capacities compared to the electricity storage, based on the assumptions in specific scenarios. It is the easiest to observe the latter in the Paper 9 of this thesis.

Finally, in [40], the authors focused on the community energy storage. Their review of the storage uses revealed that the electricity storage (Li-ion batteries) was mostly used for grid stability and load shifting, while thermal energy storage was more often used as seasonal storage. Moreover, they have shown that the energy planning in cities should shift from individual storage solutions to community storage solutions in order to have lower spikes in overall energy demand profile, to increase the round efficiency and to reduce the capital expenses [40]. Although this thesis did not focus on very short temporal resolutions that could be used to assess the grid stability issues, it has confirmed the finding from [40] about the thermal energy storage. Furthermore, the argued stance about moving to community storage solutions from individual ones was shifted even more towards the centralized solutions in this paper. Due to substantial economies of scale of storage solutions, especially in terms of thermal energy storage, it seems more reasonable to install fewer amount of larger storage systems in cities.

Future research

Future research should further focus on the optimal combination of different storage solutions also taking into account very short-term operational planning into account (temporal resolution of seconds to minutes). The latter approach could result in an increased storage capacities and/or dispatchable power needed in an energy system in order to maintain the frequency regulation and to control the voltage.

Furthermore, a detailed spatial representation of cities, including its power distribution and district energy distribution grids should allow for more detailed analysis of the optimal number and capacities of energy storage, as well as their optimal installation locations.

Finally, as this thesis reached conclusions about more relevant storage types in cities perspective, there is a need to include both thermal and gas energy storage in urban energy modelling, contrary to focusing solely on the electricity storage.

2.2.2. Import/export of electricity over the system (city) boundaries

The second flexibility option for energy system in future cities was also tackled in this PhD thesis, in Paper 6, Paper 7 and Paper 8.

In Paper 6, the power system of the municipality of Sønderborg was connected to the national grid in a model, as it is the case in the real world. That approach has also allowed for the inclusion of wind energy that would be produced outside of the municipality borders in the energy balance of the municipality itself. Moreover, a heat pump that was installed in the district heating system could be driven by electricity that could be imported from the national grid at certain points of time.

In Paper 7, the case of the city of Sønderborg also allowed for import and export of electricity over the administrative boundary of the city. Furthermore, although the location of the large-scale pit thermal energy storage, anticipated in the model, could easily be located outside of the administrative borders of the city if there would be no sufficient space for installing it inside the city. Moreover, all the CHP plants could feed their electricity towards the national grid, while a heat pump could use the electricity from the national grid.

In Paper 8, the municipality of Sønderborg was connected to the national electricity grid, being able to power an electric boiler and a heat pump located within the city boundaries during all the time periods of the year. Moreover, CHP plants could feed their generated electricity to the grid no matter what the level of demand was at specific periods of time.

General conclusion and recommendations: Allowing for the interchange of electricity over the system boundary increases the flexibility of the energy system, and that should be taken into account when modelling the energy systems of cities. It seems reasonable to assume that the net level of primary energy consumption and carbon emissions, i.e. that the emissions from energy demand, that is exported from the system at specific periods of time, are taken into calculation with a negative sign when calculating the overall energy consumption and energy emissions. By allowing the import/export of electricity over the system boundary, one can capture the behaviour of real energy systems more realistically, as well as simulate or optimize the energy system from the business-economic perspective (maximizing economic profits).

There were not enough quantitative results of this part from this PhD thesis that could bring some direct conclusions, which could serve for robust comparison against the other literature.

2.2.3. Power-to-heat and power-to-gas-to-power

Power-to-heat and power-to-gas, as well as gas-to-power, was part of the research carried out in Paper 1, Paper 4 and Paper 9. In Paper 1 and Paper 4 technologies for power-to-gas were used for estimating the viability of producing alternative fuels, so-called synthetic fuels, which can be also called electro-fuels if their production is driven by renewable electricity sources. In Paper 9, solid-oxide electrolyzers (SOEC) and solid-oxide fuel cells (SOFC) were pre-modelled in the energy system, along with the hydrogen storage. Power-to-heat technology that was used in several papers were electric boilers and large-scale heat pumps.

In Paper 1, in total 1.5 GW_e of large-scale heat pumps (average coefficient of performance = 3) was installed in the district heating systems in South-eastern Europe, while the peak heat demand for the whole region was 25.5 GW. In total 46.41 TWh of syngas (for synthetic fuels production) was generated in the region with the 5.3 GW maximum production output. The fuels were produced via syngas synthesis, while syngas was produced as a middle step via hydrogen electrolysis and carbon recycling. Synthetic fuels driven transportation vehicles met 29% of the final transport demand.

In Paper 4 it was shown that 72.3% of the transport sector at the EU level could be directly electrified with the currently available technology. Remaining part of the transport sector needs to use some other alternative, such as biofuels or synthetic fuels. Alternative scenarios in Paper 4 used synthetic diesel produced from syngas, methanol and dimethyl ether (DME). In the case of all the alternative fuels, syngas was assumed to be produced via SOEC, significantly raising the demand for electricity (and high-temperature heat). In the scenario with synthetic fuels meeting all the transport demand not being met by electricity, the additional demand for electricity and high-temperature heat was 2,775 TWh and 925 TWh, respectively. The latter number can be put in relation to the overall final electricity demand in the EU which was 3,100 TWh in 2013, as referenced in the Paper 4.

In Paper 6, heat pump with a capacity of 50 MW_{th} and an electric boiler with a capacity of 8 MW were installed in the energy system of the year 2029. In the year 2029, with all the district heating grids interconnected, electric boilers were not utilized at all and heat pumps generated 98 GWh of heat, reaching capacity factor of 22%.

In Paper 8, a heat pump with a capacity of 40 MW_{th} was installed in the case of Espoo DH and 25 MW_{th} in the case of Sønderborg. In two scenarios that included the heat pump in Sønderborg district heating, the heat pump supplied 20% of the heat. For the case of Espoo district heating, the heat pump supplied 10% of the total heat generation in the first three scenarios and a slightly lower amount in the last two scenarios.

In Paper 9, SOEC and SOFC technologies were pre-modelled, as well as electric chillers, both centralised and individual. In the Scenario 7 of the Paper 9, the one with the most stringent CO_{2e} emissions cap, 4% of the final electricity demand was met by SOFC. It is worth noting here that all the hydrogen needed for electricity generation in SOFC had to be produced by SOEC technology. Moreover, the optimal result of the Scenario 7 showed that the total installed capacity of SOEC was 1,826 MW, while the SOFC installed capacity was only 434 MW, including the 223 GWh of hydrogen storage. The latter numbers show that it was optimal to install excess capacity of electrolyzers in order to increase the flexibility of the system, helping to integrate considerable share of variable PV generation.

General conclusion and recommendations: Both power-to-heat and power-to-gas have important roles in energy supply of future cities. The most common power-to-heat technologies are electric boilers and heat pumps/electric chillers. As decentralized technologies, they have been utilized for many years now; however, there is more significant role of large-scale and centralized power-to-heat technologies. The reason is that the centralized power-to-heat technologies are easier to operate in a flexible way, according to the conditions at the power grid. Power-to-gas-to-power technologies are more seldom used but they could prove to be a promising solution for the final transition phase, both to provide grid flexibility when substantial penetration levels of variable renewable energy sources are achieved, as well as to facilitate the final transition of the heavier transportation modes in the transport sector, which are hard to directly electrify due to large energy density demands. In order to capture the role of those technologies, it is important to model the energy (supply) system in an integrated manner with captured inter-relations between different energy sectors.

Comparison with other available literature

Power-to-heat was a topic of many research papers, some of which are presented here. In [41], the authors have shown that the residential PV can also be well integrated by utilizing heat pumps and thermal energy storage, as their result showed that it was optimal to install thermal energy storage in all the scenarios. The latter finding was confirmed in this paper, especially in the Scenario 7 of the Paper 9 in which a considerable share of PV was integrated partly by the large volume of the thermal energy storage, and partly by centralized electric chillers that were used as a power-to-heat technology before the heat was stored. A very detailed and recent review of the power-to-heat technologies and their impact on renewable energy integration was carried out in [42]. Based on many reviewed papers, the authors have reached the most founded conclusions. First, power-to-heat technologies cost-effectively integrate renewable energy sources. Second, they lower the curtailment in the energy system. Third, they decrease overall CO₂ emissions compared to scenarios without power-to-heat options. Especially the first and the third points were confirmed in this PhD thesis, as in all the cases where heat pumps were used, the resulting socio-economic costs and CO₂ emissions were lower.

Moreover, the authors of [43] analysed the potential of power-to-heat technologies in the European energy system. The authors concluded that the potential of power-to-heat is significant as a demand-response technology, especially in combination with thermal energy storage, amounting to 10% of the future European peak load. However, they have stated that the potential is not evenly spread and should be assessed on a case by case basis. This PhD thesis confirmed the important role of the power-to-heat technologies, primarily of heat pumps which were used in Papers 5 to 8.

Power-to-gas evaluation for the Nordic countries was carried out in [44]. The authors assumed that hydrogen would play an important role in industry and transport sectors by 2050, with transport sector using the most significant share of hydrogen. According to the authors, between 50% and 60% of the end-use transport energy demand would be met by hydrogen in different Nordic countries, remaining part being met mostly by biofuels and a meagre share of electricity. This PhD thesis confirms the potential of hydrogen technology to serve as a last transitional step in the energy systems; however, used to a lesser degree overall than in [44]. In Paper 4, which used a bottom-up method contrary to the top-down used in [44], it was found that 27.7% of the transport sector could not be electrified and could be transitioned to hydrogen or some technology. In Paper 1, 28.6% of the end-use transport demand was met by synthetic fuels.

Another study reviewed more than 60 other studies that focused on power-to-gas technology [45]. The authors pointed out five studies that focused on 100% renewable energy penetration and which simultaneously included power-to-gas technology. Those reviewed studies had a share of power-to-gas production between 1% and 20% of the total energy demand. In the Scenario 7 of the Paper 9, the hydrogen generation had a share of 1.2% of the total primary energy demand. In Paper 1, the syngas production amounted to 6.5% of the total primary energy demand. Thus, the findings of this paper are in line with the [45].

Finally, one study focused on modelling of 10% renewable Canary island [46]. One of the scenarios included hydrogen production that would drive micro CHPs, while another scenario combined power to gas with vehicle-to-grid and demand-side management flexibility options. In the former scenario, the electricity consumed in electrolyzers amounted to 17.8% of the electricity consumption, while in the latter scenario it amounted to 12.5% [46]. In the scenario 7 of the Paper 9, electricity consumed in electrolyzers amounted to 7.1% of the total electricity consumption. As the Scenario 7 had several flexibility options, including vehicle-to-grid, demand side management in buildings and industry and power-to-heat technology, the resulting power-to-gas share matches well with the result obtained in [46].

Future research

Although power-to-heat technologies are already established ones with lots of large-scale applications, power-to-gas technologies need more large-scale demonstration projects in order to show its scalability, especially SOFC and SOEC technologies. This PhD thesis showed that if the scalability problems will be solved, and if the investment costs will fall in line with the current projections, both SOEC and SOFC could play a role in the last stages of renewable transition of the energy system.

2.2.4. Demand response

The fourth source of flexibility in the energy system was also one of the topics in several research papers, i.e. Paper 1, Paper 5, Paper 7, Paper 9 and Paper 10. Demand response was modelled only in the transport sector in the Paper 1, Paper 5 and Paper 10, while in the Paper 9 it was also modelled for the industry and buildings.

In Paper 1, smart charging and dumb charging (on demand charging) options were modelled for the electrified part of the transport sector. It was assumed that 85% of vehicles would use smart charging option, i.e. their vehicles would be charged when the conditions for it on the power grid would be optimal. The remaining part of the transport sector was assumed to be using dumb charging option, i.e. they were charged whenever they were connected to the grid.

In Paper 5, 63% of the final transport demand was electrified, in accordance to the official reports that were referenced within the paper. Out of the electrified share of the transportation, 90% was considered to be using smart charging option.

In Paper 7, thermal mass of buildings within the city of Sønderborg was used as short-term centrally activated storage, in order to make district heating supply more flexible. In different scenarios, different preheating times before the cut-off event took place were tested. The results showed that the total shifted load in the district heating sector throughout the whole year was between 20 GWh and 33 GWh in different scenarios, which can be compared with the total final district heating demand in the city of 289 GWh. By utilizing the thermal mass for storage, more solar thermal generation was effectively utilized within the system, increasing the renewable energy share of the whole energy system.

In Paper 9, in scenarios 4 to 7, i.e. the ones that did not have the upper constraint on the electrification level, 99% of the transport sector was electrified. It was anticipated that those vehicles were using the vehicle-to-grid (V2G) option, meaning that they could provide the electricity to the grid if they were connected to the grid and did not have immediate transport demand. Scenarios 4 to 6 did not utilize V2G option very often, i.e. discharge from vehicles to the grid was between 1.1% and 3.3% of the total electrified transport demand in those scenarios. However, in the Scenario 7, the one that had a substantial penetration of variable renewable energy sources, the V2G option was utilized much more, amounting to 15.5% of the total electrified transport demand. Moreover, in the Scenario 7, flexible demand was utilized 10.5% of the total potential in industry and 6.0% of the total potential in the buildings sector.

In Paper 10, in total 11.9% of the transport sector was assumed to be electrified by 2020, i.e. taxis and buses on the island. They were considered to be using smart charging, while in the sensitivity analysis V2G option was also analysed. The resulting difference in terms of curtailed energy was only marginal, i.e. the curtailed energy was reduced by 1.5% when using V2G option compared to the smart charging option. To put the latter

number in perspective, the total curtailed energy in the energy system when smart charging option was utilized was only 1.0%.

General conclusion and recommendations: Demand response is beneficial flexibility option that should be taken into account when modelling energy systems of future cities. In the transport sector, it was found that V2G option is only a marginally better option compared to the smart charging option for integration of variable renewable energy sources. However, during the modelling stages of case studies carried out in this study, initial results immediately showed that without the smart charging utilization it would be challenging to model the energy systems with a significant share of non-dispatchable sources as peak loads would significantly increase. In industry and buildings sectors, flexible demand can be a useful addition to the energy systems as they can further help to integrate more variable renewable energy sources. It was shown in Paper 9 that demand response as one source of flexibility in the energy sources does not negatively influence other flexibility sources as all demand response, power-to-gas-to-power, power-to-heat and energy storage were significantly utilized in the modelled energy system. Finally, it was shown that demand response could play an important role in district heating supply, too, and not only in the power sector.

Furthermore, this PhD thesis showed that one should not only focus on power sector when investigating demand response potential but also in the district heating supply, as it was shown that the load shifting utilization in district heating sectors could also be significant.

Comparison with other available literature

One review paper focused on energy transition scenarios [47]. The authors found that the transition scenarios failed to adequately address a critical role of flexibility in future energy systems, including demand response. This PhD thesis improved the latter by properly describing the role of demand response in different energy sectors, most significantly in Paper 7 and Paper 9. Moreover, another review paper quantitatively described contributions from different flexibility options, including demand response [48]. They found that demand response presented the best option to integrate renewables out of several flexibility options they have investigated, as it helped to increase the share of exploited available renewable energy by 17.9% compared to the base case. In the scenario carried out for the year 2029 in the Paper 7, flexible demand in district heating supply helped to integrate 12.2% more variable solar thermal energy, a result similar to [48].

2.3. Seeking for energy self-sufficiency: is there economic merit?

Out of all the papers that are an integral part of this PhD thesis, the Paper 9 dealt with the issue of modelling a city in an island mode versus modelling it in a non-island mode in the greatest detail. Scenarios 6 and 7 of the Paper 9 had a direct comparison of the energy systems in the island mode (Scenario 6) and non-island mode (Scenario 7), all other things remaining equal. There were significant differences in the optimal energy mix of the Scenario 6 and the Scenario 7. First, the optimal district cooling share was 98% in the Scenario 7, compared to the optimal district cooling share of 76% in the Scenario 6. Second, in the Scenario 6, the share of electricity generated from biomass CHP was 64%, compared to 11% in the Scenario 7. On the other hand, the share of PV generation in the total electricity generation was 33% in the Scenario 6 versus 80% in the Scenario 7. The extraordinary large share of PV generation in the overall mix resulted in a solid-oxide fuel cell electricity generation share of 4% in the Scenario 7. Third, in the thermal energy sector, the optimal share of solar thermal energy generated cold (via absorption chillers) in the total district cooling demand was 13% in

the Scenario 6 and 83% in the Scenario 7. The main reason for a much higher share of PV and solar thermal generation in the Scenario 7 compared to the Scenario 6 was that the installed capacities of those technologies were not constrained in the Scenario 7. In the Scenario 6, those technologies were constrained in capacity installed as there was not enough space available for installation of the optimal share of those technologies. The financial results showed that Scenario 7 had 18% lower total socio-economic costs than Scenario 6. Hence, by not adopting the self-sufficiency paradigm when modelling energy supply in future cities, one can achieve a significant amount of economic savings. Nevertheless, the biomass consumption in the Scenario 7 was 85% lower than in the Scenario 6, significantly reducing the air pollution levels, as can be seen from the calculated values of NO_x, SO_x and PM emissions.

General conclusion and recommendations: When modelling energy supply of future cities, a modeller should approach to the issue of the potential adoption of self-sufficiency paradigm with great care. As cities contribute to the economic activity of the nations with disproportionally large share, as well as taking into account that the energy consumption per capita in cities is more substantial than it is the case in nations overall, it is reasonable to allow for exchange of energy with the surrounding regions, as well as using the resources (including the available space for PV and solar thermal) located outside of the city administrative border. Furthermore, even if cities invest in wind energy, they should do it at the optimal wind location they can find, no matter that this is usually outside of the city borders. It does not seem conclusive that this renewable energy generation should not be attributed to the corresponding cities in that case. Finally, by using the nearby resources and exchanging energy with the surrounding regions, significant socio-economic savings can be achieved.

Comparison with other available literature

Except for the popular articles that promote self-sufficiency of energy systems in cities, there are not many scientific publications focusing on it. A research paper that focused on the urban energy generation in cities found that self-sufficiency could be a more realistic target at a regional level [49]. Furthermore, the authors have shown an example of the local energy supply company investing in renewable energy projects outside of the city boundary in order to increase the share of renewables in their portfolio [49]. The latter approach was also adopted in this PhD thesis. Finally, up to the knowledge of the author of this thesis, there were no papers that quantitatively compared self-sufficient urban energy systems versus ones that were also importing resources.

2.4. The role of district energy supply in future cities

District energy supply was in focus in several research papers of this PhD thesis. More specifically, in Paper 1, Paper 6, Paper 7 and Paper 8 district heating was in focus, while in Paper 5 and Paper 9 district cooling was in focus of papers.

In Paper 1, the total district heating demand amounted to 115.12 TWh for the whole South-east European region in 2050, which represented 58.4% of the total heating demand for the region. As this paper encompassed a vast geographical area, it is worth noting that the stated share of district heating is in relation to the total heat demand of both cities and rural areas. District heat was supplied by a wide range of different energy sources: biomass driven CHPs, industrial CHPs, biomass driven boilers, central heat pumps, solar thermal and geothermal.

In Paper 6, the topic was the potential of integrating geographically adjacent district heating grids, and the case study was carried out for the municipality of Sønderborg. The results showed that the intersectoral

integration of resources can also bring significant benefits to energy systems of the collection of smaller cities. The integrated district heating grid reduced primary energy demand for 9.5%, CO₂ emissions by 11.1% and the total socio-economic costs for 6.3%. In the municipality of Sønderborg, the share of district heating demand was equal to 52.7% of the total heating demand in the reference year and 70% in the case study carried out for the year 2029.

In Paper 7, the impact of potential utilization of thermal mass of buildings for storage and its impact on district heating supply was assessed. The case study was carried out for the city of Sønderborg, and 80% of the total heat demand within the city was met by district heating. This paper also tested several different preheating strategies as a part of the demand response investigation in the district heating sector. The latter approach is important as it was shown in the literature review of the Paper 7 that demand supply and its impact is rarely being tested in the district heating sector.

In Paper 8, impacts of dynamic pricing of district heating systems were tested for two case studies, one for Finland and one for Denmark. The latter approach was adopted in order to investigate the impact of possible marginally based pricing in the district heating systems on the integration of waste heat and other low operating cost technologies. In both case studies, the dynamic pricing of the district heating systems fostered utilization of the low cost waste heat into the grid, and it also reduced both primary energy supply and CO₂ emissions.

The following papers focused on district cooling rather than on district heating, although it was shown that the behaviour and the impact on the whole energy system of both district heating and district cooling are similar.

In Paper 5, the potential implementation of the district cooling in hot and humid climates was the main topic of the paper. The case study was carried out for the city of Singapore. The estimated district cooling potential was measured based on the available waste heat that could be used in absorption chillers for a cold generation. The waste heat was available in large amounts from natural gas driven PPs, waste incineration plants, and cold that could be directly utilized from an LNG gasification terminal. It was found that in total 168 km² of floor area could be efficiently supplied by the available district cooling potential, without additional use of central electric chillers. The total provided district cooling energy amounted to 18.45 TWh of final cooling energy demand. The holistic energy system modelling had shown that the implementation of district cooling significantly reduced the total socio-economic costs of the energy system, which was reduced even more by simultaneously implementing district cooling on PV on a large scale.

In Paper 9, district cooling was one part of the holistic smart energy systems modelling in tropical regions. Shares of district cooling and individual cooling supply were modelled endogenously. The results presented in Figure 2. of Paper 9 showed the optimal district cooling share in different scenarios. In Scenarios 6 and 7, the one that had the strictest constraints on CO₂e emissions, the district cooling share was the largest, 76% and 98%, respectively. By analysing trends of district cooling share and the whole energy generation portfolio, one can note that the optimal district cooling share is very dependable on the energy plants portfolio. The reason for relatively high district cooling share in the Scenario 6 was the large amount of excess heat available from biomass plants, that were installed in order to meet the strict CO₂e targets. The reason for very high district cooling share in the Scenario 7 was a lack of the constraint on the solar thermal capacity, which was the cheapest option in the region for supplying heat that was later fed to absorption chillers.

General conclusion and recommendations: The papers of this PhD thesis that dealt with the district energy supply showed that district heating and cooling are essential parts of the future energy system that will include lots of variable renewable energy supply. Papers that dealt with both large geographical scales, as well as the

ones that dealt with cities showed the importance of district energy supply. No paper that had pre-modelled district energy supply resulted in an optimal energy system without a certain share district energy supply. However, the Paper 9, which had the most flexible technologies modelled out of the papers of this PhD thesis, showed that the optimal share of district energy supply in cities is dependable on the energy plants portfolio in the system, mostly influenced by the available amount of excess and/or waste heat in the system. Furthermore, it was shown that district heating, as well as district cooling play very similar integration role in the energy supply of cities and that most of the conclusions about district heating in smart energy systems can be applied to district cooling in smart energy systems. Moreover, significant thermal energy storage capacities existed in all the papers that dealt with the district energy supply, confirming that it is cheaper from the system's point of view to install larger capacities of thermal energy storage compared to the grid battery storage, as shown in the Paper 9. In addition, it was shown that district heating supply should be integrated together with other energy sectors, but also within the sector, if adjacent district energy grids exist. Finally, the papers of this PhD thesis showed that district energy supply was socio-economically viable both when district energy supply grid was already installed in the system, and also when it needed to be built from scratch if a significant thermal energy demand density existed at the location. Hence, district energy supply, accompanied with large thermal energy storage capacities installed, is one of the essential integration sectors that needs to be considered when modelling energy supply of future cities.

Comparison with other available literature

The IEA's publication on sustainable urban energy systems tackled a role of district energy systems in future cities [1]. They claimed that the natural spot for installation of district heating and cooling grids is in cities, as they have energy demand density needed for such capital-intensive projects [1]. Moreover, they have argued that more distribution energy grids are needed in order to integrate raising amounts of decentralized heat generation [1]. Finally, they have presented that deregulated, open and transparent district energy markets can be found only in Sweden so far [1]. Research papers that form this PhD thesis confirmed the latter claims with quantitatively presented results. Especially the Paper 9 of this PhD thesis is suitable to examine the role of district energy in different scenarios. It is important to note that it was optimal to have a particular share of district energy supply in all of the scenarios in the Paper 9, showing its benefits on the socio-economic results of the energy system. Finally, the impact of possible deregulation, opening and making district heating markets more transparent was shown in Paper 8 of the present PhD thesis. The paper showed that dynamic heat markets value different sources of heat more realistically, especially in the future district heating supply portfolios, when more heat is generated from low marginal cost sources, such as solar thermal and industrial waste heat.

Moreover, in Heat Roadmap Europe, it was shown that carbon emissions can be significantly reduced in a cost-optimal way by deploying district heating, and heat pumps in the areas where heat demand is not large enough [50]. District heating scenario met heating and cooling demands with costs reduced by approximately 15% [50]. The latter is in line with the Paper 9 of this thesis, in which scenarios 1 and 2 brought a direct comparison of the urban energy system with individual electric chillers only (Scenario 1) and the optimal combination of electric chillers and district cooling (Scenario 2). The savings in socio-economic costs in the latter case amounted to 16%.

Another review paper on district heating tackled current and future research trends [51]. The authors stated that the future trends in district heating would include more variable renewable energy sources and the addition of new technologies that will increase the performance of the district heating systems [51]. The mentioned research directions were tackled in this PhD thesis, advancing the state-of-the-art of the district heating

research within the smart energy systems paradigm. Most notably, Paper 7 brought the case of an asset-light investment that could increase the overall storage capacity if smart controls would be installed. Moreover, Paper 8 and Paper 9 had a wide range of the investigated technologies and their impact on district heating systems operation and economics.

2.5. Transport sector and cities

The transport sector is responsible for a significant share of total energy demand in cities, and that is the sector that is the most challenging in terms of complete decarbonisation. Thus, it is an important sector when researching energy supply of future cities, and it was modelled in this PhD thesis in Paper 1, Paper 4, Paper 9 and Paper 10.

In Paper 1, the transport sector was modelled on a large scale. It was assumed, and properly referenced in the paper, that 20% of energy savings would be achieved by improved public transportation and a shift in a mode of transportation from private vehicles to the public transportation mode. Moreover, the full electrification of the railway system was assumed, as well as significant electrification of the vehicles. Out of all the electrified vehicles, it was assumed that 85% would be using smart charging option, while the remaining part would be using dumb charging option. In addition, the remaining part of the transport sector that was not directly electrified was assumed to be shifted to synthetic fuels as there was not enough sustainable biomass for the replacement of the remaining part of the fossil fuel driven vehicles.

In Paper 4, the transition of the transport sector was the main topic of the paper. As it can be hard to directly assume the share of the long-haul transport modes and aviation that should belong to the transport consumption of cities, it focused on the wide area for the estimation of the potential of the sector for the energy transition. Due to much more efficient performance of electrical engine than the internal combustion engines, as well as in order to avoid an additional conversion step and accompanied losses (as it would happen in the case of using hydrogen), the main approach was to directly electrify all the parts of the transport sector that are possible by the current technology. The results showed that the 72.3% of the transport demand at the EU level could be directly electrified, adding 880 TWh of additional demand for electricity. To put the latter number in relation, the total final electricity demand was 3,100 TWh at the EU level in 2013, as referenced in the paper. However, for the transition of the remaining part of the transport sector, energy needs are extensive. Three main alternatives were simulated, one only using synthetic fuels (electrofuels), one using only biofuels and one using a combination of biofuels and synthetic fuels. It was assumed that the synthetic fuels would be produced using electrolysis (SOEC) and different chemical syntheses in order to reach the wanted chemical composition of alternative fuels. The scenario with only biofuels used as an alternative resulted in additional biomass demand of 3,069 TWh, while the mixed scenario resulted in additional demand for biomass, electricity and high-temperature heat of 1,279 TWh, 1,646 TWh and 549 TWh, respectively. The scenario where only synthetic fuels were used as an alternative resulted in additional demand for electricity and high-temperature heat of 2,775 TWh and 925 TWh, respectively.

In Paper 9, the transport sector was modelled as a part of the integrated urban energy systems. In Scenarios 1 to 3, the transport electrification was constrained to a maximum of 10% of gasoline demand shifted to electrified transport, while other scenarios did not have an upper limit of the maximum electrification share. The result showed that in scenarios without the upper bound on the maximum electrification share, the transport sector was heavily shifted towards electrified transportation modes. The share of electrified transport in Scenarios 4 to 6 was between 92% and 93%. In the Scenario 7, the share of the electrified transport was

almost 100%. In this paper, the V2G option was modelled, meaning that the electric vehicles could bring significant additional flexibility to the grid. The latter was especially utilized in the Scenario 7, in which an equivalent of 16% of the electrified transport demand was fed to the grid in order to stabilize it, providing significant storage capacity. Finally, it was shown that the air pollution emissions, and especially health externalities connected with it, can be significantly reduced by transitioning towards the electrified transport.

In Paper 10, one part of the transport sector was assumed to be electrified, as a part of the integrated energy modelling of an island nation located in the Caribbean. The case study was carried out for the year 2020, and in total 11.9% of the total oil demand for transport was electrified, which included taxis and buses operating on the island. Moreover, as a part of the sensitivity analysis, the difference between the smart charging option and the V2G utilization was compared. The results showed that the difference between the smart charging and the V2G option on the integration potential of variable renewable energy sources was only marginal, i.e. the curtailed energy was only 1.5% lower in the case of a V2G option compared to the smart charging option.

General conclusion and recommendations: The transport sector is a critical sector that has the most difficulties when anticipating its energy transition. It is the sector with the most considerable annual growth in consumption and with the least clear goals how to carry out the energy transition. The Paper 4 of this PhD thesis, which dealt with the modelling of the transport sector on a large scale, showed that energy demand for the complete energy transition of the transport sector is significant and thus, increasing the energy efficiency, switching to the cleaner and more efficient transportation modes, as well as avoiding unnecessary travelling will also be very important. It was shown that 72.3% of the transport sector could be directly electrified and the direct electrification is the most energy efficient transition possible. This part of the transport sector will be especially relevant for cities, as travelling distances inside cities are usually smaller but more frequent, which is very suitable for electrification. Moreover, electrification of the transport sector in cities can significantly reduce the air pollution levels (NO_x, SO_x and PM), as shown in the Paper 9. Both smart charging and V2G options are attractive in terms of adding flexibility to the future energy grid that will have a significant share of variable renewable energy generation. However, additional benefits of the V2G option were found to be only marginal compared to the smart charging option, and it will be needed to evaluate the potential additional costs of faster battery ageing when the V2G option is being used. Finally, no matter what will be the final goal of the transport sector clean energy transition, the additional amount of energy demand will be large, and it will be needed to take a special precaution when modelling energy transition of the sector, both in terms of grid stability and sufficient resource availability for energy generation.

Comparison with other available literature

One research paper compared dumb charging, smart charging and vehicle to grid option [52]. Their goal was to reduce the peak load, and they did not take into account the possible availability of variable energy supply. They have shown that smart charging significantly reduced peak load compared to the dumb charging, by 71% [52]. However, the difference between smart charging and vehicle to grid option was much smaller, i.e. the peak load in the case of a vehicle to grid option was 17% lower than in the case of smart charging. Although not directly comparable, as in Paper 10 the focus was on the impact of smart charging and V2G option on energy supply (i.e. on curtailed energy) and not on energy demand, it seems that the benefits of the V2G option in [52] were higher than in Paper 10 of the present PhD thesis.

Concerning the more general research, the IEA's report on sustainable urban energy systems concluded that the three main options to make the energy systems sustainable by 2050 is to avoid transport altogether, to shift transport modes to less carbon-intensive ones and to improve vehicle efficiency and reduce the carbon

intensity of fuels [1]. Furthermore, they claimed that the most important role of local authorities is to introduce policies that will reduce air pollution [1]. Technological analysis carried out in the Paper 9 on air pollution confirmed the latter claim on air pollution from [1], as it was clearly shown that non-point source pollution from vehicles had the most substantial negative external costs imposed on society. Concerning the three main options to make the energy systems more sustainable, this PhD thesis adopted the modal shift of the transport sector, most notably in Paper 4. The present PhD thesis further showed that the largest energy efficiency gains in urban energy systems occur via transport electrification. The latter could be seen from both Paper 4 and Paper 9.

Future research

The most concerning question rising from this PhD thesis is the transport transition of the part of the transport sector that cannot be directly electrified by the currently available technology. Especially Paper 4 showed how large resources would be needed if the switch to biofuels and/or synthetic fuels (electrofuels) would become a reality. Synthetic fuels production would substantially increase the transport connected primary energy demand of the part of the transport sector that cannot be directly electrified, contrary to the needed energy efficiency gains. Although there are still no proven solutions, a further shift towards electrification of the heavier transportation modes, including ships, should be tested, as direct electrification proved to be the most energy-efficient option.

2.6. Other technologies: the role of water desalination, energy efficiency and prosumers from the system's point of view in future urban energy systems

Several different technologies were also included in this thesis although with less strong focus. One of them is **reverse osmosis for water desalination** that can be run flexibly and consequently, increase the flexibility of the energy system. As reverse osmosis consumes around 3.5 kWh of electricity per m³ of desalinated water, it can significantly increase demand in periods when there is a surplus of generated electricity. Water desalination was part of the Paper 9 and Paper 10.

In Paper 9, the overcapacity of reverse osmosis in the optimal energy system in Scenarios 1 to 3 was in the range of 2.1 to 4.6%. In the Scenarios 4 to 6, the overcapacity was 9.5%, 8.1% and 5.8%, respectively, while it was almost non-existent in the Scenario 7. The increased overcapacity of the reverse osmosis technology correlates with the significantly increased electricity demand for transportation. In the Scenario 7, the optimal solution included solid-oxide electrolyzers and fuel cells, which proved to be cheaper option to increase flexibility when there was a large capacity of installed PV, along with the large share of transportation sector electrified.

In Paper 10, the reverse osmosis technology was allowed to be run flexibly as an overcapacity existed in the energy system. The overcapacity of the installed reversible osmosis technology was 38% compared to the average daily demand. Excess capacity of the reverse osmosis consumed 0.9 GWh of electricity or 0.13% of the total yearly electricity demand, which means that the curtailed energy was reduced by the same amount.

Finally, it can be recommended for future modelling of energy supply that reverse osmosis should be allowed to run flexibly in the models, as that is one of technologies that can increase flexibility of the system in an economically beneficial way. Especially the Paper 9, in which the capacity of reverse osmosis was not

constrained but was rather the result of the optimization, showed that adding a certain overcapacity of reversible osmosis to the energy systems can reduce the overall socio-economic costs.

Prosumers were another topic of several of the papers. Prosumers are consumers of energy that generate energy at specific points of time and feed it back to the energy system. Prosumers in this PhD thesis were modelled in the district heating sector, mostly in terms of waste heat fed into the grid, and in the transport sector, when the V2G charging option was utilized, allowing for the electricity to be fed back to the grid from batteries installed in electric vehicles. Prosumers were part of the Paper 6, Paper 8 and Paper 9.

In Paper 6, tilework factories could feed the waste heat back to the district heating systems. In total, 33.89 GWh of estimated waste heat from factories could be fed to the district heating grid over the year, representing 6.9% of the total final district heating demand in the reference year. Cases VIII and IX included the waste heat potential in the energy system, and they both resulted in lower primary energy supply, reductions in CO₂ emissions and the total system cost.

In Paper 8, waste heat fed from prosumers to the district heating grid was part of several scenarios in both case studies. In the case of Sønderborg, waste heat was part of the Sønd WH, Sønd WH SDH, Sønd WH SDH HP and Sønd ALL scenarios. Especially the Sønd WH scenario is useful for reaching conclusions, as the inclusion of waste heat was the only variable that changed compared to the Sønd ref scenario. The inclusion of waste heat in the district heating market set-up based on marginal pricing resulted in a lower yearly turnover, as well as lower weighted average marginal price. In the case of Espoo, waste heat from data centres accompanied with heat pumps was part of the Espoo WH, Espoo GEO+WH and Espoo GEO+WH+STOR scenarios. Comparing the Espoo WH with the Espoo REF case, one can again note that the total yearly turnover, as well as the weighted average marginal heat price reduced. Furthermore, other scenarios of the paper show that lots of low marginal cost heat technologies could start to compete in the district heating system, especially in periods with lower heat demand during summers.

In Paper 9, prosumers were mainly in the form of vehicle owners, as V2G charging option was utilized. The results of different scenarios showed that the V2G option was mainly utilized in the Scenario 3, with a relatively small share of electrified transport, and in the Scenario7, with a very high share of variable renewable energy installed (PV). Thus, prosumers in the form of vehicle owners can contribute to the flexibility of the energy system, especially when a significant share of electricity demand is met by variable renewable energy sources.

However, as already pointed out, the sensitivity analysis carried out in Paper 10 showed that the difference between the smart charging and V2G option was only marginal, at least in the system that is dominated by both PV and wind production and with relatively small share of electrified transport sector. Hence, it will be important to assess whether the cost of implementing the V2G option on the vast scale will be lower than the benefits of introducing prosumers in the transport sector.

Finally, **energy efficiency** is another important topic, especially when focusing on cities. Energy efficiency can be looked at on both supply and demand sides of the energy system. On the demand side, energy efficiency, such as better insulation and less consuming appliances can reduce the final energy demand. On the other hand, better handling, integrated planning, and more efficient energy plants are some of the measures that can reduce the primary energy demand or reduce the conversion losses. Energy efficiency was one of the topics in Paper 1, Paper 4, Paper 5, Paper 6 and Paper 9.

In Paper 1, the large-scale modelling revealed that if serious energy efficiency efforts would not be undertaken, there would simply be lack of renewable energy sources available for the full transition to a sustainable energy

system. Some of the assumed measures were efficiency increase in buildings performance resulting in reduced thermal energy demand by 50% until the year 2050, major replacement of individual heating supply systems with district heating in order to utilize more of the waste and excess heat available, increased energy efficiency in industry of 2% per year per unit of output, and 20% of energy efficiency improvement in the transport sector achieved by switching to more energy efficient transportation modes. All those measures, including better-optimized energy supply, resulted in 50.7% lower primary energy demand in the year 2050 compared to the reference year.

In Paper 4, it was shown how transport electrification could bring significant energy savings to the system. For example, in 2013, the final energy demand in the transport sector of the EU was 4,057 TWh, as referenced in the paper. As it was calculated that 72.3% of the transport energy demand could be directly electrified, 2,931 TWh of oil demand could be reduced to 880.3 TWh of the electricity demand for the same travelling distance. Thus, direct electrification of the transport sector can bring significant energy savings.

In Paper 5, the energy efficiency of the supply side of the energy system was in focus. It was shown that district cooling adoption could lead to a 7.3% lower primary energy demand. Moreover, by combining district cooling with increased penetration of PV would lead to the 19.5% lower primary energy demand compared to the business-as-usual scenario. Savings would be mainly achieved by utilizing waste heat from gas plants and waste incineration plants in absorption units which would replace the individual cooling demand.

In Paper 6, increased energy efficiency was achieved by integrating distributed district heating grids, which allowed for better utilization of more efficient energy plants. Interconnecting geographically distributed district supply grids lowered primary energy supply by 9.5%, reduced carbon emissions by 11.1% and lowered total system costs by 6.3%. The inclusion of industrial prosumers reduced primary energy supply in the interconnected grid for an additional 2%. Thus, it can be seen that intersectoral integration can also significantly increase the energy efficiency of the energy system.

In Paper 9, an improved energy efficiency occurred in both supply and demand sides of the energy system. On the demand side, four energy efficiency investments were pre-modelled, according to the calculations of the official energy efficiency roadmap of Singapore, as referenced in the paper, and the solution of the model could pick one of them. In scenarios 5 to 7, it was allowed to undertake a certain energy efficiency option and the result was always the same, the option that introduced 22.3% of the energy savings was chosen as optimal. On the supply side, primary energy supply differed significantly in different scenarios. In scenarios 2 to 5, which presented a stepwise integration of more and more energy sectors, primary energy supply reduced with each step. In the Scenario 6, the one that imposed the strictest constraint on CO_{2e} emissions, the primary energy supply increased due to lower efficiency of biomass electricity generation. In the Scenario 7, primary energy supply increased due to different reasons. First, due to energy accounting method used, solar thermal heat energy utilized in absorption chillers can have lower efficiency compared to individual electric chillers driven by electricity generated in gas plants, as discussed in the paper. Second, biomass CHP met 11% of the final electricity demand, which also caused relative increase in primary energy demand compared to the gas CHP plants.

Hence, it can be concluded that primary energy supply reported as one number *per se* is not enough to conclude about the efficiency of the energy supply. Due to different accounting principles, low cost and vastly available renewable heat can appear to increase energy consumption compared to the fossil fuel driven thermal energy generation. It is especially important to take into account that heat pumps (electric chillers)

usually only report electricity consumed as the total energy consumption, resulting in reported efficiencies above 1.

Energy efficiency measures can definitely deliver positive socio-economic results, as shown in several of the papers. It is important to focus on energy efficiency on both supply and demand sides of the energy system. Especially papers that focused on the large scale modelling in this PhD thesis showed that the renewable energy sources are scarce and should be consumed carefully in order to allow for the complete energy transition. On the other hand, especially Paper 9 showed that it is not always economically optimal from the overall system's perspective to invest in energy efficiency as much as possible, as in all the scenarios the optimal energy efficiency investment was in the middle range of the savings. When modelling future energy supply of cities, it is important to find the right balance between the energy efficiency measures, renewable energy supply and district energy supply and not to focus on only one of those sectors too heavily. The Paper 9 of this PhD thesis further showed that different constraints, such as targeted CO₂e emissions, significantly influence the optimal mix between energy efficiency, renewable energy supply and the share of district energy, which should be clearly presented to the policy makers and any other relevant stakeholders.

3. Perspectives and outlook

The broad topic on energy supply of future cities, covered in this PhD thesis, answered some questions and opened many others. Urban energy systems are becoming more and more complex, and future models will need to cover even more interacting variables. It was shown that large shares of variable renewable energy sources could be successfully integrated into energy systems in both short and longer investment time horizons. The flexibility needed to incorporate large shares of variable renewable energy sources is provided in the easiest and socio-economically cheapest way if a holistic approach is taken in energy modelling. Moreover, different case studies carried out in this thesis, for both smaller and larger cities, showed that an energy transition is possible in different urban set-ups. Respective solutions will differ based on many different variables, including the energy demand density and the available resources.

However, several different issues arose from this thesis that need to be further dealt with. The first one is the role of biomass in future cities, the questions of its carbon neutrality and the air pollution emissions connected with the use of it. This thesis further reinforced the concerns about the negative externalities imposed by air pollution. Biomass consumption is of concern here as it can present a sustainable energy source in terms of climate change, if the carbon neutrality paradigm is adopted, but can still be unsustainable in terms of air pollution emissions and negative externalities of air pollution. The concern about the carbon neutrality of biomass was raised in this thesis, and further research on this topic will be needed. Finally, even if the carbon neutrality of biomass is accepted, suitability of biomass use in many different energy sectors will make this resource very scarce, and thus, integrated energy planning of different sectors needs to be carried out in order to assign right shares of biomass to different sectors in an optimal way.

Second, both district heating and district cooling can play an important role in integrating variable renewable energy sources in cities. This thesis showed in different papers that district cooling can play a similar integrating role of variable energy sources as district heating in future energy systems. Both district heating and district cooling development can open the playing field for more efficient utilization of waste heat, in the form of the

prosumers. Thus, the role of prosumers in future district heating and district cooling systems is an important point that needs to be further researched, based on the findings of this PhD thesis.

Third, roles of district heating and district cooling bring us to the role of different storage types in future urban energy systems. In several of the papers attached to this thesis, it was shown that optimal capacity of thermal energy storage in urban energy systems is often significantly higher than capacities of other storage types. The thermal energy storage in both district cooling and district heating grids can successfully smooth the variability of renewable energy sources such as wind, PV and solar thermal, providing the needed flexibility to the energy system. Furthermore, future urban energy models, with more detailed spatial resolution, will be able to reveal the optimal mix of centralized and decentralized energy storage. This thesis showed that centralized energy storage would play an essential role in future urban energy systems due to the economy-of-scale; however, decentralized storage can play an important role in congestion management in both power and thermal energy systems. Nevertheless, this thesis further showed that when focusing on storage modelling of future urban energy systems, both gas and thermal energy storage need to be included, along with battery storage, in order to find an overall energy system optimal solution. Finally, the present thesis showed that building thermal mass for storage could play a complementary role to large-scale thermal energy storage in future urban energy systems. The latter fact is important as thermal mass for storage can be considered as a light investment in storage, contrary to the usually capital intensive storage investments.

Fourth, it was shown in this thesis that many different demand response technologies could play an important role in future urban energy systems. It was further shown that energy supply and demand could not be modelled separately if different demand response technologies are to be successfully included. The present thesis further showed that demand response technology could have a significant beneficial impact on the district heating supply too, and not only on the power system supply. Hence, future research should implement those findings and model demand response technologies in district heating and district cooling sectors, too.

Fifth, modelling of several different energy systems, both on a smaller scale (cities) and larger scale (regions) showed that upon the successful implementation of a substantial share of variable renewable energy sources in the energy system, certain capacities of power-to-gas-to-power technologies appear in the optimal set-ups of future energy systems. However, in order for different power-to-gas-to-power technologies to be economically feasible in real urban energy systems, successful large-scale demonstration projects will need to be carried out, including SOEC and SOFC, among other technologies. One of the scenarios of Paper 9 showed that optimal capacities of SOEC and SOFC were 1,826 MW and 434 MW, respectively, for the case of Singapore. The latter numbers show that from the system point of view, capacities of power-to-gas-to-power could be much larger than the currently demonstrated projects.

Sixth, power-to-gas-to-power technologies bring us to the issue of the final phase of the energy transition in the transport sector. This thesis showed that everything that can be directly electrified in the transport sector should be electrified due to at least two reasons. First, it increases the energy efficiency of the overall energy system as electric motors have much higher efficiencies than internal combustion engines. Second, it reduces local non-point source emissions, improving the air quality in cities. The part of the transport sector that cannot be directly electrified is a challenging one in terms of energy needs for its transition. Both biofuels and/or synthetic fuel production as potential solutions will be challenging in terms of utilizing available resources in a sustainable way, due to the very large demand for those alternatives. Thus, heavy transport, shipping and air transportation modes, and their transition towards cleaner alternatives should be further researched, but from a system point of view, taking into account competition for scarce resources from other energy sectors, too.

Some questions were answered by this thesis, and many were opened by the presented results. Although there is a lot of research that needs to be carried out further in the field of the urban energy transition and future urban energy supply, successful solutions could result in climate-friendly, clean, secure and affordable future urban energy systems. Rapid urbanization that is taking place across the globe makes the urban energy transition towards cleaner alternatives a necessity. Swift reaction, careful holistic planning and proper implementation of technological advances can direct the cities towards the clean energy development, avoiding the harmful and expensive lock-in effects in the initial phases. This PhD thesis contributed to solving a wide range of issues that occur in complex urban energy systems and hopefully encouraged *you*, the readers, different stakeholders and researchers to further investigate issues and detect beneficial solutions for successful urban energy transition.

4. Collection of papers that form the present PhD thesis

Paper 1 - [Zero carbon energy system of South East Europe in 2050.](#)

Dominkovic, Dominik Franjo; Bačeković, I.; Ćosić, B.; Krajačić, G.; Pukšec, T.; Duić, N.; Markovska, N.

In: Applied Energy, Vol. 184, 2016, p. 1517–1528.

Annual report year: 2016

Paper 2 - [Economic feasibility of CHP facilities fueled by biomass from unused agriculture land: Case of Croatia.](#)

Pfeifer, Antun; Dominkovic, Dominik Franjo; Ćosić, Boris; Duić, Neven.

In: Energy Conversion and Management, Vol. 125, 2016, p. 222-229.

Annual report year: 2016

Paper 3 - [Waste to energy plant operation under the influence of market and legislation conditioned changes.](#)

Tomic, Tihomir ; Dominkovic, Dominik Franjo; Pfeifer, Antun; v, Daniel Rolph ; Pedersen, Allan Schrøder; Duić, Neven.

In: Energy, Vol. 137, 2017, p. 1119-1129.

Annual report year: 2017

Paper 4 - [The future of transportation in sustainable energy systems: Opportunities and barriers in a clean energy transition.](#)

Dominkovic, Dominik Franjo; Bačeković, Ivan; Pedersen, Allan Schrøder; Krajačić, G.

In: Renewable & Sustainable Energy Reviews, Vol. 82, No. Part 2, 2017, p. 1823-1838.

Annual report year: 2017

Paper 5 - [Potential of district cooling in hot and humid climates.](#)

Dominkovic, Dominik Franjo; Rashid, K. A. Bin Abdul; Romagnoli, A.; Pedersen, Allan Schrøder; Leong, K. C.; Krajačić, G.; Duić, N.

In: Applied Energy, Vol. 208, 2017, p. 49-61.

Annual report year: 2017

Work carried out during the guest research stay at NTU, Singapore.

Paper 6 - [On the way towards smart energy supply in cities: The impact of interconnecting geographically distributed district heating grids on the energy system.](#)

Dominkovic, D. F.; Bačeković, I.; Sveinbjörnsson, D.; Pedersen, A. S.; Krajačić, G.

In: Energy, Vol. 137, 2017, p. 941-960.

Annual report year: 2017

Paper 7 - [Utilizing thermal building mass for storage in district heating systems: Combined building level simulations and system level optimization.](#)

Dominkovic, D. F.; Gianniou, P.; Münster, M.; Heller, A.; Rode, C.

In: Energy, Vol. 153, 2018, p. 949-966.

Annual report year: 2018

Paper 8 - [Influence of different technologies on dynamic pricing in district heating systems: Comparative case studies.](#)

Dominkovic, Dominik Franjo; Wahlroos, Mikko; Syri, Sanna; Pedersen, Allan Schrøder.

In: Energy, Vol. 153, 2018, p. 136-148.

Annual report year: 2018

Paper 9 – [Modelling smart energy systems in tropical regions.](#) / Dominkovic, D. F.; Dobravec, V. ; Jiang, Y.; Nielsen, P. S.; Krajačić, G.

In: Energy, Vol. 155, 2018, p. 592-609

Annual report year: 2018

Paper 10 – **Integrated energy systems of island countries**

Dominkovic, Dominik Franjo; Stark, Greg; Hodge, Bri-Mathias; Pedersen, Allan Schrøder.

In: Energies (submitted to)

Annual report year: 2018

Work carried out during the guest research stay at NREL, Golden, Colorado, the USA.

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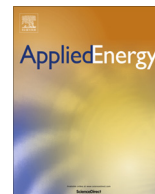
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APPENDIX – Full papers that form the PhD thesis

Paper 1 - Zero carbon energy system of South East Europe in 2050

Dominković DF, Bačević I, Čosić B, Krajačić G, Pukšec T, Duić N, et al. Zero carbon energy system of South East Europe in 2050. Appl Energy 2016. doi:<http://dx.doi.org/10.1016/j.apenergy.2016.03.046>.

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Zero carbon energy system of South East Europe in 2050



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HIGHLIGHTS

- 100% renewable energy system of the South East Europe has been achieved.
- Sector integration makes the zero carbon system cheaper compared to the base year.
- Numerous renewable technologies needed to achieve zero carbon in the year 2050.
- Energy efficiency is a crucial part in a transition to the zero carbon energy system.
- No technology has a larger share than 30%; increased security of energy supply.

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ABSTRACT

South East Europe is the region in a part of Europe with approximately 65.5 million inhabitants, making up 8.9% of Europe's total population. The countries concerned have distinct geographical features, various climates and significant differences in gross domestic product per capita, so the integration of their energy systems is considered to be a challenging task. Large differences between energy mixes, still largely dominated by fossil-fuel consumption, make this task even more demanding.

This paper presents the transition steps to a 100% renewable energy system which need to be carried out until the year 2050 in order to achieve zero carbon energy society. Novelty of this paper compared to other papers with similar research goals is the assumed sustainable use of biomass in the 100% renewable energy system of the region considered. It is important to emphasize here that only the sustainable use of biomass can be considered carbon-neutral. The resulting biomass consumption of the model was 725.94 PJ for the entire region, which is in line with the biomass potential of the region. Modelling the zero-carbon energy system was carried out using the smart energy system concept, together with its main integration pillars, i.e. power-to-heat and power-to-gas technologies. The resulting power generation mix shows that a wide variety of energy sources need to be utilized and no single energy source has more than a 30% share, which also increases the security of supply. Wind turbines and photovoltaics are the main technologies with shares of 28.9% and 22.5%, followed by hydro power, concentrated solar power, biomass (mainly used in cogeneration units) and geothermal energy sources. To keep the biomass consumption within the sustainability limits, there is a need for some type of synthetic fuel in the transportation sector. Nevertheless, achieving 100% renewable energy system also promises to be financially beneficial, as the total calculated annual socio-economic cost of the region is approximately 20 billion euros lower in the year 2050 than in the base year. Finally, energy efficiency measures will play an important role in the transition to the zero-carbon energy society: the model shows that primary energy supply will be 50.9% lower than in the base year.

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1. Introduction

Countries in the South East Europe (SEE) region have been facing various common problems related to the energy sectors. Energy markets are generally small and energy prices are below economic level, while countries' economies are energy intensive.

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Furthermore, tariff structures are undeveloped and poor infrastructure as well as history of conflicts complicate energy trade in the region [1]. Therefore, regional cooperation of the SEE countries, integration of energy systems and harmonization of legislations is necessary. In order to increase security of supply, economic efficiency and use of renewable energy sources (RES), which are important for future energy systems, as well as to reduce market concentration, common energy system has to be created [2]. Nevertheless, transition to clean renewable energy systems can be beneficial in economic, energy-environmental and sociological terms [3].

With the population of approximately 65.5 million inhabitants, SEE region makes around 8.9% of Europe's total population [4]. An average median age of the population in the year 2014 was 39.8 years, which is about 6% below the average of the European Union (EU28) [5], while the rate of population older than 60% was 22%. Urban population accounts for 59% of the total population in the region: Bulgaria having the highest rate of urban population with 75%, while the lowest share has Bosnia and Herzegovina (B&H) with 50%. The region recorded depopulation between years 2013 and 2014 at a level of 0.14%, which is largely due to the fact that the total number of emigrants from SEE countries was 77,342 [4]. Differences in economic development within the region are significant, since the highest gross domestic product (GDP) per capita of 23,962\$ records Slovenia and the lowest GDP of 3877\$ has Kosovo, also the Europe's youngest country [6]. Therefore, average GDP per capita of 9922\$ is only 28% of the EU28 average. Great differences can be noticed in geographical characteristics and climate conditions as well. Region consists of several main geographical features, from mountain chains such as the Alps, Dinarides and Carpathians extending through Slovenia, Croatia, B&H, Serbia, Montenegro and Kosovo to the Mediterranean and Ionian Sea in Greece and Adriatic Sea in Croatia, Montenegro and Albania. Total area of the region is 765,884 km², Romania being the largest country by far with 238,391 km² (or 31% of the total area), while Slovenia and Montenegro are the smallest, with 20,256 km² and 13,812 km², respectively. Average population density is 85.5 people/km², which is 23.6% lower than the EU28 average [6]. Southern part of the region, with a moderate climate and dry summers with a large number of sun hours, distinguishes from northern and eastern part's continental climate, with long and hot summers, but also cold and intensive winters [7].

State of the art of regionally integrated energy systems, and impacts of the integration on countries involved, is described in the following articles. Authors in [8] analyse the advantages of regionally integrated electricity supply system in comparison with power generation system of individual countries in the Western Africa. Results show that integrated system has 38% lower total electricity production compared to individual systems. The advantages of inter-regional integration of electricity market for the case of East China have been analysed in [9]. Results demonstrate that electricity utilities in the inter-regional electricity market dispose with larger generation capacity, while market can benefit from more optimal usage of resources and capacity. Challenges of greater regional energy co-operation in the South Asia region, one of the fastest growing regions in the world, have been discussed in [10], while social cost-benefit analysis of two electricity interconnector investments in Europe has been conducted in [11]. In [12] authors show how the cross-border electricity transmission has a significant importance when a country or a region has an increased electricity production from intermittent RES. Furthermore, author in [13] describes the case of Nordic countries, the world leaders in electricity production from RES, which achieved successful regional cooperation which should be followed by other countries and regions. Analysis in [14] shows that the penetration level of RES is highly determined by the flexibility of the system.

Finally, in order to reach the goals from [15], storage and balancing synergies have to play an important role in future energy systems.

Evaluation of reliability of Integrated Energy System (IES) has been conducted in [16]. Authors analysed IES as a regional energy system that includes various sub-systems, such as electricity, gas, heating and cooling, and other energy supply systems. Importance of integration of electrical and heating systems, in order to facilitate implementation of RES, is also emphasized in [17]. Authors concluded that cooperation between these two sectors can reduce fuel consumption and energy losses. Novelty in this paper is interplay between transport and industry sectors with energy supply systems (heat and electricity), which increases possibility to integrate even more fluctuating RES and reduce fuel consumption and losses further.

In [18] author provides an overview of the electricity production systems in 10 countries in SEE during 1995–2004 and investigates the potential of integration of electricity markets. Author concludes that an efficient regional energy market would help to meet peak demand in individual countries and significantly increase reliability and stability of electricity supply across the region. However, it emphasizes high level of dependency on hydro and thermal (fossil and nuclear) electricity production. Congestion management methods, as well as infrastructural transmission assets in the region are described in [19]. This paper also stresses importance of establishing regional electricity market in order to allow more cost-effective electricity production. European Union electricity reform is explained in [20], together with its relation to the SEE electricity market. Paper expresses doubts that EU model is completely applicable and good for SEE region. Furthermore, The Energy Community, experiment in a creation of regional energy market between the EU and SEE partners, is described in [21]. Achievements in the process of establishing a stable market framework and regulation conditions within the Energy Community are described in [22]. Here author also emphasizes importance of the SEE regional electricity market formation as a first step towards the integration with the EU market. Within the 2030 Climate and Energy Policy Framework, European Commission stated the target of achieving 15% of existing electricity interconnections for Member States which have not yet accomplished a minimum level of integration in the EU energy market by the year 2030 [23]. Furthermore, importance of cooperation between countries, governments, energy planners and utilities on both financial and policy side in order to achieve economic growth when implementing RES is discussed in [24]. Abovementioned papers present state of the art of energy system integration in SEE, with the focus on policies to further integrate the region in the EU market.

Several papers deal with the planning of low-carbon energy systems with a high share of RES. In [25] author describes approach in creating 100% renewable energy systems that are technically feasible, sustainable in terms of bioenergy use and economic competitive with fossil fuels. Furthermore, authors in [26] presented a planning method of the 100% independent Croatian energy system with the special emphasis on RES, energy storage technologies and different regulation strategies. In their work, they reached 78.4% share of RES and significant CO₂ emissions reduction, concluding that in order to achieve 100% independent or 100% RES, a detailed planning of all sectors has to be carried out. Similar research has been conducted in [27], where 100% renewable energy system for the case of Macedonia is presented as possible, but only with a different storage technologies. However, in that scenario usage of biomass is too high taking into account the national potential, so it was concluded that 50% renewable energy system in the year 2050 is much more realistic. Beside traditional uses of RES, there is a vast potential to exploit new and emerging technologies such as high altitude wind energy [28]. High potential of implementing this type of renewable energy in SEE region has been proved in

[29]. Potential for biogas production in one county of Croatia using a bottom-up methodology was assessed in [30]. Authors in [31] created three scenarios to reduce CO₂ emissions in Western Europe by 96%, with the shares of 40%, 60% and 80% electricity production from RES. Transition of Mexican electricity system from fossil fuels to RES has been presented in [32]. In order to meet the goals set by the Mexican Congress, authors created three high-RES scenarios and achieved 35% RES electricity production in the year 2024, including sustainable use of biomass. However, they focus only on the power generation sector and the latter does not include plans for the year 2050. Furthermore, three scenarios for two countries in South East Asia for the year 2050 have been created in [33]. Focus was on transition of electricity sector towards RES in order to reduce CO₂ emissions. As a result, they achieved the RES share of 40% of total electricity production in Indonesia and 39% in Thailand. Novelty in this paper presents a 100% renewable energy system that includes integration of power, heat, gas and transport sectors in SEE.

Majority of the papers mentioned above focus solely on the integration of electricity markets in SEE, excluding benefits from the cross-sector inter-regional integration. Exception is [34], where 100% renewable SEE has been modelled. However, in their work too much emphasis was put on power system, which led to unsustainable use of biomass. Consumption of 1670 PJ of biomass was calculated, while the sustainable potential is equal to only 730 PJ (Bulgaria, Greece and Romania [35], Albania, B&H, Croatia, Macedonia, Montenegro and Serbia [36], Kosovo [37], Slovenia [38]). Furthermore, excessive investment in pumped hydro storage (PHS) was assumed (increase of 15.6 GW h), which will be hard or almost impossible to meet taking into account PHS potential as calculated in [39]. Improvement in the modelling approach in this paper compared to [34] is the sustainability in usage of biomass, which is met by a number of interactions between different sectors of the energy system.

Thus, the novel approach shifts the focus from sectoral to a holistic view when modelling different energy sectors, such as power, heat and gas systems (including mobility), augmented with the regional integration of energy system (geographical integration). This approach leads to the detection of synergies between different sectors and areas which would remain undetected by solely focusing on partial solutions, such as smart grids, which allows more intermittent energy sources to be integrated in the energy system. Furthermore, it makes transition to zero-carbon energy system feasible considering only locally sustainable potential of the biomass, as opposed to studies where biomass import over the system boundaries is allowed.

Another novelty is that the integration of 100% RES energy system is planned for regions that are parts of the same synchronous electricity network and interconnected gas grids, but having different political systems. Five of the analysed countries are EU member states, four candidate countries and two potential candidates. The majority of them are members of European Network of Transmission System Operators for Electricity ENTSO-E and the European Network of Transmission System Operators for Gas ENTSO-G, while several countries act as observers in these associations. Planning of 100% RES system in this way can show another benefit for mutual cooperation and bonding on energy system planning.

Scenarios are developed for the reference year, which was set in this paper to 2012, and for the year 2050. The modelling tool used in this paper is EnergyPLAN. In the year 2050 the whole region is considered to be 100% renewable. In this paper the SEE region consists of eleven countries: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Greece, Kosovo, Macedonia, Montenegro, Romania, Slovenia and Serbia.

The goal of this paper is to model a zero carbon energy system in a technically feasible way (critical excess in electricity production needs to be less than 5%, while the system is modelled as a

closed one, setting transmission capacity with the neighbouring countries to zero), using realistic measures and penetrations of specific technologies, not exceeding their technical potentials. Furthermore, the system needs to be robust and thus, it should not depend heavily on one technology; it should rather contain mix of different technologies. Finally, the total socio-economic cost should be as low as possible, keeping in mind that the system should be technically possible and realistic to achieve. Further novelty in this paper is that the 100% renewable SEE will be modelled by consuming biomass in a sustainable way, i.e. within the limits of biomass potential in the region.

Section 2 of the paper is dedicated to the description of the methodology and EnergyPLAN model, after which the case study and scenarios have been described in Section 3. Results of the case study are presented in Section 4, while the discussion part focuses on the comparison of the results with the other state of the art work. Finally, sensitivity analysis is carried out for the case of extremely dry year, in order to assess the consequences of reduced hydro power plants production and possible water scarcity due to climate change, followed by the main conclusions.

2. Methodology

In this paper, the concept of smart energy systems is adopted. Contrary to the concept of smart grids, where emphasis is put only on one part of the energy system, the power sector, the concept of smart energy system detects and utilizes synergies between different sectors of energy system, i.e. power system, heating sector and gas grid [40]. Moreover, in order to adopt smart energy system concept correctly, biomass has to be used in a sustainable way and thus, only certain part of forest residue should be used as a primary energy source. A model, specially developed for modelling of smart energy systems is EnergyPLAN, developed at Aalborg University [40].

Today, many different models for energy planning exist. A great review of energy planning tools is given in [41]. According to it, out of many tools only seven of them incorporate electricity, heat and transport sectors, while only four of them have already simulated 100% renewable energy system, i.e. EnergyPLAN, MesapPlaNet, INFORSE and LEAP. In this study, hourly analysis is preferred as it allows detecting instabilities in the power grid, as well as the nature of critical excess in electricity production, its frequency and the magnitude. Out of mentioned four modelling tools, only EnergyPLAN and MesapPlaNet have the possibility of hourly time steps simulation. Furthermore, MesapPlaNet has a very small number of users [41] and it was used only in Greenpeace studies for simulation of 100% renewable energy system in the year 2007 [42], 2008 [43], 2010 [44] and 2012 [45]. On the other hand, EnergyPLAN is already a well-established tool for modelling 100% renewable energy systems. It was used for modelling of 100% RES in the following countries: Portugal [46], Macedonia [27], the Netherlands [47], Latvia [48], Ireland [49], Croatia [26] and Denmark [50]. Overview of several 100% renewable energy systems modelled was given in [51]. Furthermore, the model was used for the assessment of the 100% renewable EU28 [52]. As it satisfies all the needs for this study, EnergyPLAN was chosen to be a modelling tool for calculating 100% renewable SEE in the year 2050.

The EnergyPLAN model is a detailed input/output model. Inputs that need to be set are energy demands in general, renewable energy sources, energy conversion units such as electrolyzers, energy plant capacities, costs and a regulation strategy. Outputs are energy balances and resulting annual productions, fuel consumption, import/export and total costs including income from the export of electricity [53].

Concerning the total system cost as an output of the model, it can present a socio-economic costs or business economic costs.

The socio-economic costs were used as an output in this paper, which encompasses levelized investment costs of the energy plants over their lifetimes, fuel costs, fixed and variable operating and maintenance costs, as well as CO₂ taxes as environmental externality. It is worth mentioning here that taxes in general are not included in the calculation of socio-economic costs as they are considered to be only internal redistributions within the society. Furthermore, costs of implementing energy efficiency measures or advising costs of consulting companies during the preparation phase of the projects are not incorporated in the socio-economic cost in this paper. However, although implementing energy efficiency measures can impose high upfront costs, they will be offset by the savings in energy spending. Hence, in the long term these measures will actually lower the total socio-economic costs even more than calculated here.

Detection of health consequences and job creation opportunities are externalities that remained outside of the scope of this paper when determining total socio-economic costs, although inclusion of these figures would gain more beneficial results for renewables dominated energy system. In support of the latter statement, authors in [54] calculated that the transition towards renewable energy system in China in the year 2050 would create 4.12 million jobs. Furthermore, including currently externalized health costs of the Danish heat and power sectors would decrease total health costs by 18% [55]. It has been showed on the case of Taiwan in [56] that the net benefits of avoided premature deaths, averted morbidity, savings in social costs and years of life lost are equal to 118,279 million USD during the period 2010–2030.

The model simulates energy system behaviour during one year in hourly resolution (8784 steps) and thus, it is a suitable tool for analysis of intermittent RES, as well as the hourly, daily and seasonal fluctuations in energy demand.

The model can be applied from the municipality levels to the European level. The model describes the interaction between the

combined heat and power (CHP) plants and the RES especially well, in the same time allowing the interplay between the heating and power systems. By various means interplay between gas grids and the heating and electricity systems is well modelled, too [53].

On the other side, constraints of the model are its aggregated approach to power plants' modelling, where all the thermal power plants are represented by the total capacity and fuel distribution percentages between coal, natural gas, oil and biomass. Similarly, heat storages and district heating plants are modelled only in three groups, which can possibly cause misinterpretation of the modelled system due to the geographical constraints that can occur in the real system. Furthermore, the system is treated as a single point without internal congestion management modelling. As a consequence, it cannot be clear from it whether there are disbalances and congestion in transmission and distribution networks between different regions and/or countries. Also, it is important to emphasize that the model does not distinguish between different types of biomass. An important comparison between optimization model such as TIMES and simulation model such as EnergyPLAN has been presented in [57].

The complete system interactions of the model can be seen in Fig. 1.

Technical simulation will be used in the model, which seeks to find the solution with the minimum consumption of fuels, i.e. with minimum emissions of CO₂.

3. Case study: Zero carbon SEE in the year 2050

3.1. Reference energy system (2012)

Reference energy system was built for every country independently, validated against the International Energy Agency's data [58] and then joined together in the one energy system.

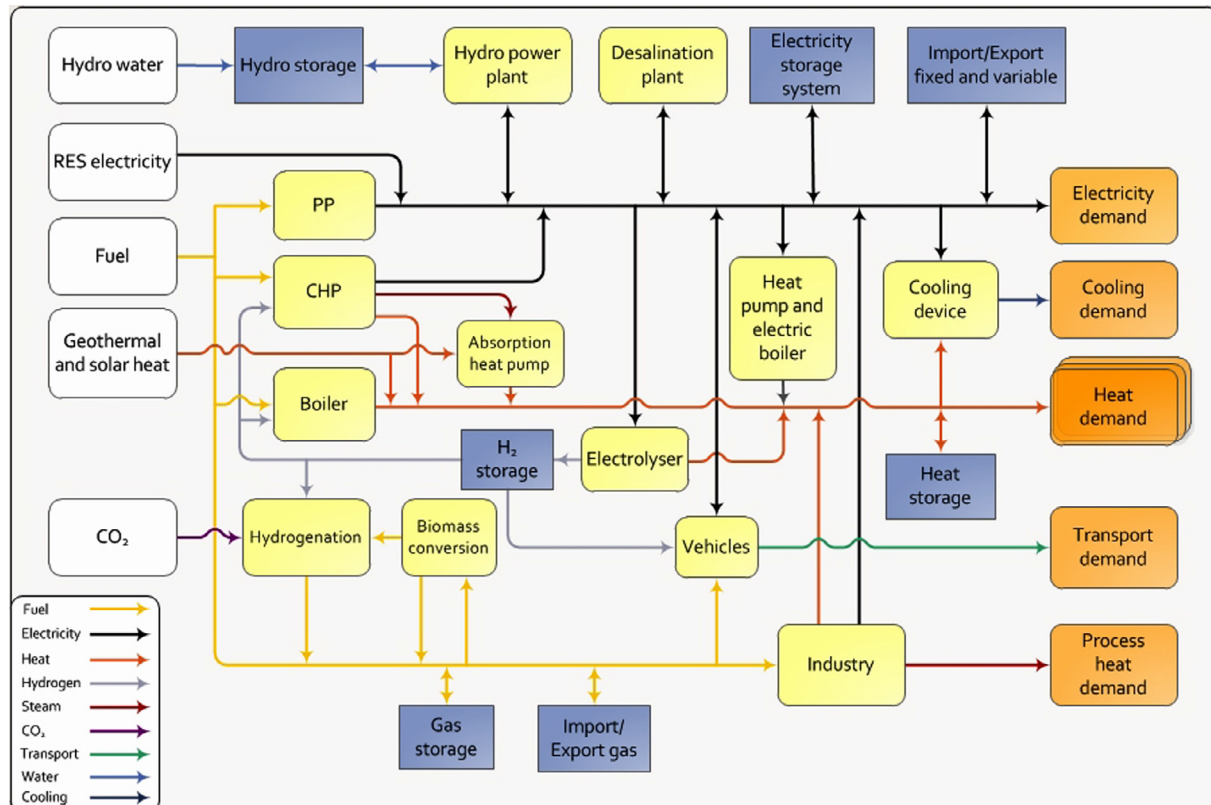


Fig. 1. The EnergyPLAN model in version 11.4 [40].

Table 1

Installed generation capacity in the SEE region.

Country	Year	Ref.	Hydro [MW]	Thermal [MW]	Nuclear [MW]	Biomass [MW]	Wind [MW]	PV [MW]	Other RES [MW]
Albania	2012	[62]	1450	0	0	0	0	0	0
B&H	2012	[63]	2034	1590	0	0	0	2.4 [64]	0
Bulgaria	2012	[65]	2864	6613	2000	20 [66]	684	908	0
Croatia	2012	[67]	2136	1681	0	13.8	180	4	0
Greece	2012	[65]	2817	9741	0	39	1865	1039	0
Macedonia	2012	[68]	578	800	0	0	0	1.6	0
Montenegro	2012	[69]	660	208	0	0	0	0	0
Romania	2012	[70]	6195	9460 [71]	1300	89	1905	51	0
Serbia	2012	[72]	2910	4642	0	0	0	0	0
Slovenia	2012	[73]	1254	1495	696	41	2	240	0
Kosovo	2012	[74]	43	885	0	0	0	0	0
Total	2012		22,941	37,115	3996	202.8	4636	2246	0

Electricity data was obtained from ENTSO-E [59], except for Albania and Kosovo, countries for which the electricity data is not available on ENTSO-E. Demand for these countries was calculated by obtaining monthly demand values from [50,51] and scaling it on hourly resolution using the average of other SEE countries' profiles. As these two countries represent only 7% of the total population in SEE, this assumption will not cause a significant impact on overall results. Heat demand was calculated using the degree-hour method, while the hourly temperatures were obtained from [60]. Solar radiation curves, river hydro and dammed hydro distribution profiles were used for the year 2008 [40] and adapted to the yearly values of hydroelectric power plants generation obtained from the International Energy Agency (IEA) [58].

Wind speed data was obtained from EnergyPLAN database of measured data for the year 2008 [25] and adapted to the capacity factor in 2050 as calculated in [61]. As showed in [45,46], average yearly wind speed is usually between the 10% range from the mean and seldom in the range of 20% from the mean for the specific location. Furthermore, as the system modelled is not excessively dependent on wind (less than one third of the electricity generation), it is assumed that the system is robust enough to deal with these small fluctuations between different years. Moreover, as the modelled geographic area is large, the differences in annual wind speeds for a specific location flattens out when many wind farm locations are considered.

Economic data, which includes investment costs, energy plant lifetimes, fixed and variable operating and maintenance costs were taken from the official website of the model developers [40]. The cost database is constantly being updated and can be freely accessed. Discount rate was set to 3% and CO₂ emissions cost in the year 2050 is set to 46 €/ton. However, the latter number does not have any influence upon the result as the system in 2050 is already the zero-carbon one.

The majority of capacity in SEE is linked with thermal and hydroelectric power plants, i.e. 37.8 and 23.1 GW. Out of total capacity of hydroelectric power plants, 83.6% are dammed power plants (including cascade power plants), while 16.4% are run-of-river hydro power plants. Nuclear power plants are installed in Romania, Bulgaria and Slovenia with the total capacity of nearly 4 GW. Wind energy is a dominant RES technology with installed capacity of 4.6 GW in 2012, followed by photovoltaics (PVs) with installed capacity of 2.2 GW.

A detailed list of power plants for each country for the year 2012 can be seen in Table 1.

The CO₂ contents of 74 kg/GJ for fuel oil, diesel and petrol, 56.7 kg/GJ for natural gas and 101.2 kg/GJ for coal have been used in the analyses [40].

3.2. Zero carbon energy system in 2050

Building a 100% renewable energy system, while consuming biomass in a sustainable way consists of several steps.

Firstly, power and district heating sectors need to be integrated in order to allow more than 20% of intermittent electricity production (wind and PVs). The integration of these two sectors needs to be achieved by advanced CHPs and heat pumps coupled with thermal energy storage, in order to increase efficiency of the system and reduce the overall fuel consumption. Secondly, electrification of majority of light vehicles needs to be introduced. Vehicle-to-grid (V2G) technology needs to be implemented in order to help balancing out the electrical grid. Moreover, where possible, pumped storage hydroelectric power plants need to be installed to further improve integration of intermittent energy sources. A next step is penetration of wind power and PVs on a large scale, especially as for the latter technology a significant drop in investment costs is anticipated. Furthermore, other RES such as waste incineration power plants, small hydro power plants and concentrated solar power with thermal storage (CSP) are introduced. In the heating sector, it is especially important to introduce geothermal energy on a large scale.

In the transportation sector, medium and heavyweight vehicles which cannot be electrified by current battery technology need to be fuelled by either biofuels or electrofuels. As technologies for electrofuels are still not in the commercial phase, majority of transportation means is assumed to be driven by biofuels or synthetic fuels produced from biomass.

In individual heating sector, parts of houses and buildings which cannot be connected to district heating grid need to be heated by heat pumps or solar thermal energy. If none of these technologies are suitable, individual biomass boiler technology will still be used.

Overview of measures on the demand side of the model and references of each implemented measure can be seen in Table 2. On the other hand, measures implemented on the supply side of the system are presented in the Table 3.

4. Results

Analyses were made in EnergyPLAN looking at SEE as a closed system and thus, transmission capacity to neighbouring countries was set to zero. Thus, all the generated excess electricity was considered to be a critical one and abbreviation CEEP is used to denote it (Critical Excess in Electricity Production).

4.1. Reference scenario validation

In order to validate the model, reference scenario made for the year 2012 was validated against the data obtained from the IEA [58].

As it can be seen from Table 4, the reference model developed for the year 2012 matches well with the data obtained from the IEA. The total CO₂ emissions differ 3.5%, while total primary energy

Table 2
Measures on the demand side of the system.

Measure	Ref.	Discussion
Efficiency increase in individual houses by 50%	[75]	In Energy Efficiency scenario of Energy Roadmap 2050 a staggering 72% of increased efficiency is assumed; it is assumed here that it is exaggerated, as it was argued in [52] and thus, 50% of increased efficiency is assumed
Energy efficiency increase of 50% in households supplied by district heating	[75]	In Energy Efficiency scenario of Energy Roadmap 2050 a staggering 72% of increased efficiency is assumed; it is assumed here that it is exaggerated, as it was argued in [52] and thus, 50% of increased efficiency is assumed
Replacement of 52.5% of individual heating houses with small scale district heating (1.5% per year)	[52]	In Heat Roadmap Europe 2050 an increase in DH from 12% to 50% is assumed for the same period. As the penetration in the base year for SEE is already higher than 20%, it is assumed that it is viable to achieve the penetration of DH of 51.5%. Furthermore, in [76] it was shown that small scale biomass driven cogeneration system is economic feasible investment if pit thermal energy storage is used for peak purposes instead of boilers
50% of final heating demand of houses not connected to the DH is met by heat pumps, 20% by solar thermal and 30% by biomass boilers	[77]	Measures adopted from the references with slightly higher share of biomass adopted as it is expected due to the much larger penetration of biomass nowadays that a slightly larger share will it have in the year 2050
In industry, increased efficiency of 2% per year is leveled out with the same increase in industrial activity, which is set to 2% per year in average for the whole region	[52]	Measure adopted from the reference without any modifications. There are many measures for increase of energy efficiency in industry, e.g. [78] showed the possibility of achieving energy savings of 8.2% in a crude distillation unit using the process integration techniques
20% of demand in industry is met by industrial CHPs	[52]	Measure adopted from the reference without any modifications
15% of demand is met by solar thermal energy with storages	[79]	According to the reference share of solar thermal energy in industry could reach up to 33%. More conservative approach was assumed in this paper and a share of 15% has been adopted
45% of energy demand of fossil fuels in industry is replaced with electricity	[80]	New efficient induction furnaces are coming to the market. As shown in the reference, induction plant can replace conventional gas or oil-fired furnace, significantly reducing the consumption of fuels and as a consequence lower the greenhouse gas emissions (GHG). Thus, it is assumed that a large portion of energy intensive industries will shift to induction furnaces
Remaining coal and oil consumption is replaced by biomass	[77]	Measure adopted from the reference without any alterations
In transport sector 20% energy savings needs to be achieved by improved public transportation system and replacement of one part of individual vehicles with public transportation (mainly electrified trains)	[77]	Measure adopted from the reference without any alterations
Total electrification of railway system	[77]	Measure adopted from the reference without any alterations
100% of light transport vehicles and 35% of medium transport vehicles is replaced by electrical vehicles; out of these 85% will be using smart charge system, while 15% dumb charge system	[77]	Measure adopted from the reference without any alterations
Remaining part of transport sector demand is met by synthetic fuels produced mainly by chemical synthesis from biogas (hydrogenation of biomass); 25% of fuel demand is met by CO ₂ hydrogenation using electricity as energy input	[81]	As using biomass (e.g. rapeseed) for biofuels has been criticized due to the competition with the food supply chain, land use impacts [82], sustainability problem and impacts on land resources [83], a hydrogenation of biomass was introduced as it uses less biomass from biofuels and better integrates intermittent RES in the system [81]

supply differs for 1.4%. It can be also seen that resulting fuel emissions are slightly different in the reference model compared to the IEA data, as the difference in CO₂ emissions is slightly greater than the primary energy supply (PES) difference.

4.2. Comparison of energy systems in years 2012 and 2050

In Fig. 2 the total primary energy supply for the year 2012 and 2050 can be seen. In 2050, the whole energy supply is renewable and the total biomass consumption is sustainable, i.e. its consumption is equal to 201.65 TWh. Biomass potential in all countries for the year 2012 can be seen in Table 5.

Thus, modelled biomass consumption is within the biomass potential. According to the reference [98], 71% of the total potential of sustainable biomass in Western Balkans (Albania, B&H, Croatia, Macedonia, Kosovo, Montenegro and Serbia) is attributed to woody biomass (i.e. residuals from wood industry, logging residuals, residuals from pruning different fruit trees, olive trees or vineyards and firewood) and 29% to agricultural biomass (i.e. food-based and nonfood-based portions of crops such as wheat, barley or corn residuals). Therefore, the same share can be used for the SEE region in this case.

In Fig. 3, detailed renewable energy generation by sources can be observed.

The largest share in electricity production have wind and PVs with 28.9% and 22.5%, followed by dammed hydro, CSP, biomass driven plants (mainly CHPs), geothermal and river hydro. It is important to note that none of technologies exceed 30% of generation share on yearly basis, which shows that the system is robust and is able to cope with fluctuations in generation of specific technologies between the different years. Moreover, large geographic scale of integrated energy system of SEE evens out fluctuations of certain generation technologies at a local level.

It is interesting to compare generation of electricity on hourly resolution during the two days in summer and winter, which is presented in Fig. 4:

It can be seen that PVs are dominating the generation mix during the summer. Beneficial feature of the power system during the summer is that PV production corresponds to the peak consumption. In the summer day during the evening and night, the majority of generation comes from dammed hydro plants. Furthermore, it should be noted that the pump hydro plants are working during the night with the maximum capacity in the turbine regime, which adds 2 GW of power generation capacity, helping to meet the overall electricity demand as the night in the mid-July being presented had very low wind production.

During the winter, generation of PVs is on a much lower scale. Dammed hydro production had a large share of generation during

Table 3

Measures on the supply side of the energy system.

Measure	Ref.	Discussion
Total capacity of wind set to 50 GW	[61,84]	According to the references, the total economic viable wind potential is 137 GW. However, more conservative approach has been adopted. (Greece, Romania and Bulgaria [84], other SEE countries from [61])
Total capacity of PVs set to 65 GW	[61]	According to the reference, up to 50% of final electricity demand could come from PVs in this region
Total capacity of CSP set to 11 GW	[85]	According to the reference Spain installed 1.3 GW of CSP from 2006–2012. Thus, 11 GW of CSP in the SEE till the year 2050 was assumed as a viable estimate. (2020–2030 2.5 GW, 2030–2040 3.5 GW and period 2040–2050 5 GW of installed capacity)
Increase in dammed hydro power capacity for 25%, to 23.5 GW	[86]	According to the reference, technical and economic feasible potential in this region is still huge and hydropower could be increased by more than two times. However, due to complicated procedure when building dammed hydro much more conservative approach has been adopted
Introduction of 1.5 GW _e of large scale heat pumps	[87–89]	As it was shown in the references, large scale heat pumps are beneficial technology (to solve intermittency and efficiency problems [87], beneficial in cooperation with CHP systems [88] and beneficial in implementing high share of RES [89]) for integration of intermittent RES and thus, this technology has been introduced
13.3% of heat in DH system is met by solar thermal with a 75 GW h of seasonal thermal energy storage	[90]	According to the reference, in municipality of Sønderborg in Denmark a 20% of DH demand is projected to be supplied by solar thermal. Due to the much larger systems and higher winter peaks, a smaller share of solar thermal has been assumed to stay on the safe side
All newly introduced district heating goes to the small scale networks	[76]	It was shown in the reference that small scale DH networks are economic feasible in current support system, as well in Feed-in premium system
Installation of 230 GW h of seasonal storage in DH network	[91,92]	In Zagreb, a seasonal storage of 750 MW h has been built already [91]. However, due to the large return temperature losses are higher than usual and the real capacity of this storage in optimal regime is 1.5 GW h. In Ref. [92] it was shown that in Denmark already today a three times larger storages exist. Thus, it is assumed that each country will build four storages with equivalent size of the storage built in Marstal, Denmark with the capacity of 5 GW h
960 MWe and 2.38 GW h of waste incineration power plants	[52,93]	Calculated from Heat Roadmap Europe and scaled due to the population ratio of SEE and EU28 [52]. It is assumed that similar amount of waste is produced per person. However, to be on the safe side the total potential has been reduced by 20%. Technical data for waste incineration plant was obtained from Energinet's report [93]
1250 MWe of geothermal PP	[94–96]	Technical potential (Croatia and Greece [94], Bulgaria and Romania [96], Albania, B&H, Kosovo, Macedonia, Montenegro, Serbia and Slovenia [95]) adopted without any alterations
Adding 7.5 GW of geothermal heating energy (in 2050 40% of heat in DH is produced by geothermal energy sources)	[94–96]	Technical potential (Croatia and Greece [94], Bulgaria and Romania [96], Albania, B&H, Kosovo, Macedonia, Montenegro, Serbia and Slovenia [95]) adopted without any alterations
Increase in river hydro and small hydropower plants to 6.8 GW	[86,97]	According to [86], SEE utilizes only 41% of economic hydro potential. Furthermore, [97] estimates much higher potential for each individual country. However, conservative approach has been adapted to be on the safe side
Increase in CHP capacity to 8 GW	[52]	Adopted according to the reference.
Reduction in thermal power plants capacity to 24.7 GW and replacing its fuel with biomass	[50]	Adopted according to the reference. The capacity of thermal power plants, as stated in Table 1, is assumed to be gradually reduced towards 24.7 GW, decommissioning the old thermal power plants upon the end of their lifetimes
Decommission of all nuclear power plants		Due to inflexible operation, high capital costs and already long operation time it is also not envisaged to have new installations after 2025
Introduction of 11 power plants similar to Avča (total new storage 1067 GW h (obtained from [39], pumping capacity 1980 MW and turbine capacity 2035 MW)	[39]	Storage within 5 km distance from the lower lake has been taken from the reference as a viable potential

Table 4

Validation of reference model.

	IEA SEE (TWh)	EnergyPLAN SEE (TWh)	Difference IEA – EnergyPLAN (%)
Coal	466.4	468.3	–0.40
Oil	438.3	437.8	0.12
Ngas	256.5	256.9	–0.15
Nuclear	99.6	99.5	0.15
Hydro	49.1	49.7	–1.26
Biomass	113.2	113.8	–0.55
Other	23.0	0.0	
CO ₂ (Mt)	320.7	332.0	–3.52
PES	1446.2	1426.0	1.39

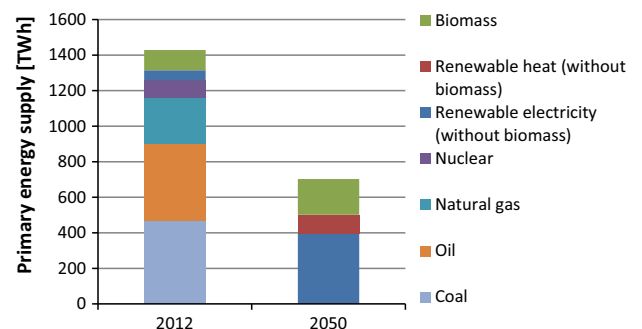
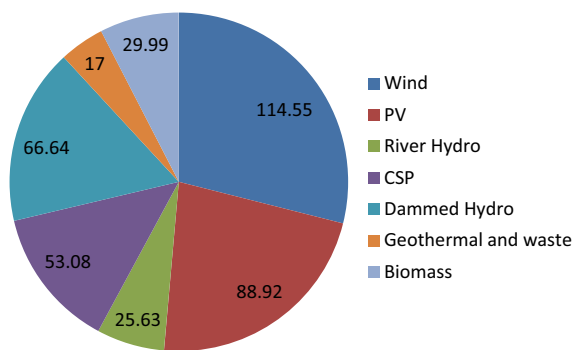
**Fig. 2.** Primary energy supply in the year 2012 and 2050.

Table 5

Biomass potential of countries located in SEE (Bulgaria, Greece and Romania [35], Albania, B&H, Croatia, Macedonia, Montenegro and Serbia [36], Kosovo [37] and Slovenia [38]).

Biomass potential	PJ	TWh
Slovenia	19.6	5.4
Greece	27.10	7.5
Croatia	56.14	15.6
Montenegro	12.03	3.3
Serbia	136.8	38.0
B&H	56.41	15.7
Albania	29.79	8.3
Kosovo	4.85	1.3
Macedonia	21.61	6.0
Bulgaria	44.36	12.3
Romania	318.03	88.3
Total	726.74	201.9

**Fig. 3.** Mix of renewable electricity generation in the year 2050 [TWh].

the evening. However, during the night in winter period, dammed hydro production is lowered down due to the higher generation of wind energy. Moreover, the peak demand and the trough demand do not differ as much as during the summer period.

Finally, evaluation of the energy system from the technical point of view in the year 2050, compared to the current system

(2012), can be assessed by taking a closer look at the data presented in Table 6.

It can be seen from Table 6 that the primary energy supply has decreased significantly (50.7%), while the CO₂ emissions reduced to zero in the year 2050. Critical excess in electricity production is equal to 15.64 TWh or 4.4% of the total electricity production. However, it is important to note here once again that the system of the SEE was modelled as a closed system, without transmission to the neighbouring countries. By using different strategies, such as gasification and production of synthetic fuels when there is an excess in electricity production, CEEP can easily be reduced for 50%. Nevertheless, further decrease in CEEP can be achieved by introducing the transmission capacity to the neighbouring countries [99]. It is worth mentioning here that besides having 100% renewable energy system in the year 2050, the total annual socio-economic cost is almost 20 billion EUR lower in the year 2050 compared to the reference year. Thus, although higher costs can occur during the initial phases of transformation to the 100% renewable energy system due to the high upfront costs, the final energy system can be cheaper compared to the one heavily dependent on fossil fuels.

5. Discussion

In [76] authors presented biomass driven trigeneration system coupled with pit thermal energy storage on a case study for one district in Croatia. They have showed that building small scale cogeneration units can be beneficial in economic terms. This approach has been also confirmed in this model, as small scale CHP systems increase fuel efficiency of the system and thus, decrease the total biomass consumption. Furthermore, along with the heat pumps and thermal storage, CHP plants are used to integrate heating and power sectors which leads to further increase in efficiency.

In [100] the influence of energy policy on energy demand was assessed on a case study of Croatia. By inclusion of policy measures in different scenarios, achieved energy efficiency improvements equalled to 23% in industry, 25% in households and 27% in trans-

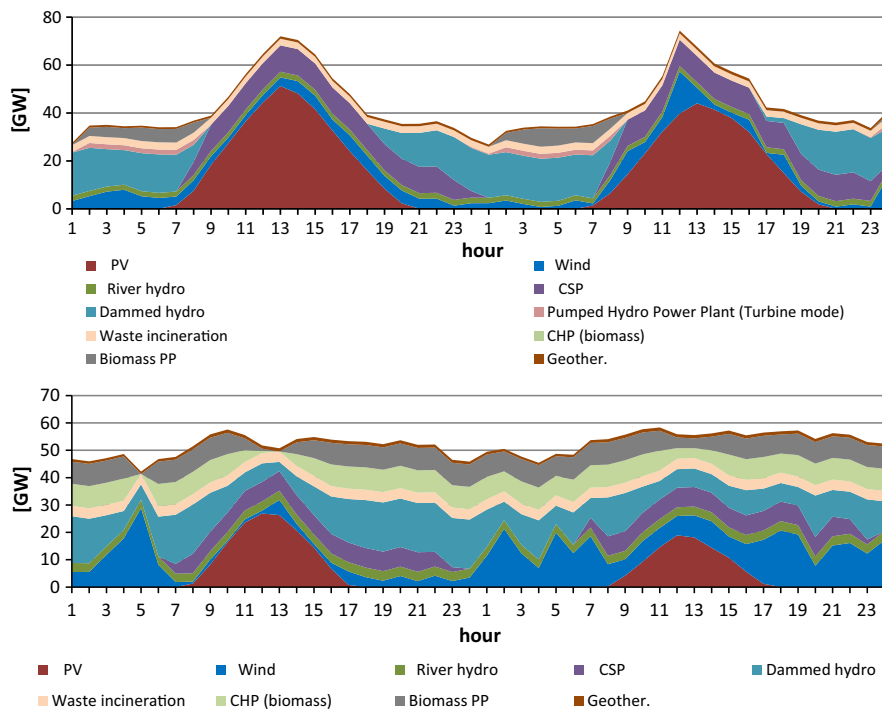
**Fig. 4.** Electricity generation mix during two days in mid-July (up) and in the beginning of January.

Table 6

Comparison of different parameters of energy systems in the year 2012 and 2050.

	2012	2050
PES [TWh]	1426	702.86
CO ₂ emissions [Mt]	332	0
CEEP [TWh]	0	15.64
Total annual socio-economic cost [MEUR]	63,903	44,415

portation sector. Total savings in PES after the measures were adopted equalled 22%. Moreover, overall biomass consumption for the case of Croatia is not completely clear so the sustainability in usage of biomass remained unclear.

In this paper, measures proposed in several different papers for the case of Denmark, Energy roadmap 2050 and Heat roadmap 2050 were adapted or directly adopted. Moreover, certain energy efficiency goals proposed in Energy roadmap 2050 were argued as exaggerated and measures from other references were adopted. By using referenced energy efficiency measures in this paper, a total primary energy savings equalled to a significant 50.7%. Although the expenses for increased energy efficiency measures are greater in the beginning, the total socio-economic costs for the year 2050 will be lower.

In [61], the biomass consumption was unsustainable, as already shown in the introduction, and the excessive investment in pumped hydro storage was assumed. Furthermore, primary energy supply is equal to 943.6 TWh and the largest share in electricity consumption has wind (34%), followed by PV (20%), river hydro (14.4%) and pumped hydro plant (14%) generation. Yearly modelled biomass consumption amounts to 1690 PJ. Reported CO₂ emissions in 2050 are equal to zero while primary energy supply is 33.8% lower compared to the reference year (2008).

In this paper total primary energy savings are equal to 50.7%, 726 PJ of biomass is consumed annually and pumped hydro storage is increased only till its technical limit as referenced in Table 3. Thus, PES in this paper is 34% lower and the biomass consumption is 57% lower than in [61]. This proves that greater energy efficiency of the system can be achieved by the better integration of the whole energy system, compared to the solely focusing on the power sector. Furthermore, biomass consumption in integrated energy system can be reduced to the sustainable level.

It is of crucial importance to clarify that the statement “*the better integration of the whole energy system*” refers to the integration of power, heating and gas sectors (including transportation), complemented with the regional integration (geographical integration) of the energy systems. This integration leads to the better technical system in terms of managing the intermittent energy sources and robustness of the modelled system in general, as well as to cheaper energy system considering the socio-economic costs. On the other hand, taking only power sector into consideration, in so called smart grids, leads to the partial solution that cannot detect possible synergies between different energy sectors. As a consequence, the latter approach will lead to either more expensive system in terms of socio-economic costs or to less viable energy system from technical point of view, represented in the ability to integrate intermittent renewable energy sources.

The possibility of carbon capture and storage (CCS), coupled with coal fired thermal power plant in the SEE has been assessed in [101]. The ultra-supercritical pulverized coal power plant with and without CCS was assessed. Authors have used levelized cost of electricity (LCOE) assessment for showing the viability of investment in the power plant. In the case without the CCS, the calculated LCOE was 57.25 €/MW h, while in the case with installed CCS the LCOE was 92.42 €/MW h. Assumed carbon price was 10 €/tCO₂, while the assumed running times of the power plant

were 7200 h and 7600 h. In the sensitivity analysis authors have shown that reduction in availability of 10% can increase the LCOE cost for up to 6 €/MW h. It would be even more interesting to see the calculated LCOE with the running time of around 5000 h (35% reduction in availability), as it can be assumed that the LCOE result would be even worse.

The latter finding is crucial here. The electricity price is formed on market according to the supply and demand. Supply curve is built according to merit order of every power plant. Power plants bid their offers according to variable costs of electricity generation and in the case of PVs, wind energy, run-of-river hydro and CSP this cost is zero. Thus, power plant which uses fuel, such as coal, needs to make its offer at some higher price as it least needs to cover the costs of fuel and other variable costs. When there is a lot of electricity production from wind or solar energy, the marginal cost of electricity will be very low, much lower than the cost of electricity generation from coal power plant. This leads to the conclusion that there will be many hours when electricity generation is dominated by wind and solar sources (as shown in Figs. 3 and 4), forcing the coal fired power plants to be shut down in these hours. As a result, coal fired power plants will have much lower number of running hours throughout the year than assumed in [101], which results in economic unfavourable indicators. Although in some countries of SEE the El-spot market still has not been set in place, it is expected that this will happen in the near future and thus, investment in coal power plants, both with or without CCS, will be economic unviable. Because of this reasoning, new coal fired power plant investments should not be considered when planning the future energy system development.

Authors in [102] presented the methodology developed in the RE-SEETies: “Towards resource efficient urban communities in SEE” project, focusing on overview of urban energy and waste management systems of communities in SEE. They suggested integrated, transnational approach to promote RES and energy efficiency measures. The project resulted in many recommendations for successful implementation of energy efficiency measures, increase of public acceptance for RES and waste handling (both recycling and waste-to-energy).

Many recommendations and findings in the mentioned paper coincide with the measures proposed in this paper. Some of these measures are: increase in energy efficiency, waste-to-energy utilization, RES penetration, choosing ambitious goals, transnational (regional) cooperation and integrated approach in transformation of energy system towards a low-carbon one. It can be concluded that both papers strive towards the sustainable society and are mutually complementing. This paper deals more with the technical side of the problem and the pathway towards reaching the 100% renewable energy system, while [102] puts more emphasize on the implementation of specific measures and recommendations for cooperation between different stakeholders.

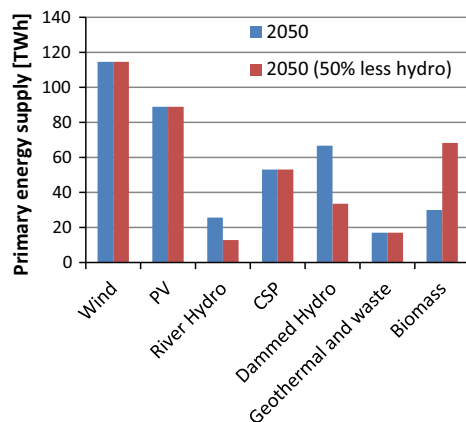
Thus, compared to the previous papers with case studies being done in the region of SEE, it is shown in this paper that integrated and holistic approach to the whole energy system can open the space for the detection of additional benefits for the system which can improve the system from technical point of view. Furthermore, a holistic approach when adopting certain energy efficiency measures or measures on promotion of certain technologies on the supply side of the energy system can reduce the total annual socio-economic costs of the energy system.

Technical calculations are just the stepping stone but joint energy planning can have more benefits as in the case of electricity and gas transmissions system planning. To have a common policy, such as achieving zero carbon systems for SEE, can have benefits in terms of security of investments, economies of scale, joint public private partnerships and technology development, especially

Table 7

Comparison of results obtained in sensitivity analysis.

	2050 50% less hydro	2050
PES [TWh]	748.4	702.86
CO ₂ emissions [Mt]	0	0
CEEP [TWh]	13.85	15.64
Biomass Consumption [PJ]	1044	726
Total annual socio-economic cost [MEUR]	47,900	44,415

**Fig. 5.** Difference in electricity generation during sensitivity analysis.

towards sustainable energy technologies such as ecologically harmless hydropower plants. All these benefits need to be further elaborated and addressed in the further research.

6. Sensitivity analysis

As shown in [67] for the case of Croatia, hydro power plants production can deviate from the mean value for up to 47%. Although in the last decade the highest extremes were showing during the wet years, the sensitivity analysis will be carried out assuming that the extreme will show up during the dry year. As similar conditions appear in all the countries of the region, a sensitivity analysis with 50% less production of hydro power plants has been carried out.

As it can be seen from Table 7, during the extremely dry year biomass consumption can become unsustainable. Moreover, during the dry year additional space for renewable technology such as wind can occur. Increase in biomass consumption during the dry year equals to a significant 43.8%. In Fig. 5, it can be seen that there is no capacity in other renewable technologies and biomass driven plants need to take over all the missing hydro production.

Thus, in order to achieve the sustainable use of biomass on projected extremely dry year, an additional capacity of renewable technologies should be installed. However, the projected dry year is a real extreme and the 'savings' in biomass during the wet year can cover the unsustainable use of biomass during the dry year. This reasoning stems from the research carried out for the case of Norway in which was shown that the wet years occur three times more frequently compared to dry year [40].

Moreover, long-term melt-down of glaciers in Austrian Alps can cause increased flow in downstream rivers, which can increase hydropower potential during the melting season from May to October as shown in [103]. However, ever increasing melting rate of snow can reduce its ability to serve as accumulation, which can cause floods and more intermittent production of hydro power

plants. By this example it can be seen that climate modelling is crucial in planning of future energy systems.

7. Conclusion

In this paper, energy system of SEE has been analysed. It was clearly shown that 100% renewable energy system of the whole region is possible by taking many steps in different sectors during the transformation phase to zero carbon society. Furthermore, to achieve 100% renewable energy system, and in the same time sustainable in terms of biomass consumption, integration between different sectors of energy systems is needed in order to increase overall efficiency of the system. By integrating energy systems, carefully interacting within them and investing in heating energy storage, serious savings in primary energy consumption can be achieved. It is of great importance to maximally utilize cheap gas and heating energy storage (compared to electrical one), as well as electrical storage in vehicles, following V2G concept, in order to have the attractive system from economic point of view, too. Following these steps, a developed renewable energy system of the SEE consumed 702.86 TWh of primary energy, 50.7% less compared to the year 2012. Furthermore, the system reached zero-carbon emissions in a technically viable way as the CEEP remained below the 5%, i.e. it was 4.4%. The modelled power system is robust as neither of generation technologies exceeds 30% of the total generation mix. Among them, wind and PV are dominant technologies with the generation shares of 28.9% and 22.5%, respectively. Installed thermal capacity is reduced from 37.1 to 24.7 GWs, its yearly load factor is 14.8% and they are completely driven by biomass. The load factor of these plants does not need to be high as their use in the future system is only to cover the periods when there are no fuel-free generation options available. Finally, integrated regional energy system of the future has 30.5% lower total yearly socio-economic costs compared to the current system.

In order to consume biomass in a sustainable way, some type of synthetic fuel is needed. In this paper, the chosen technology was hydrogenation of biomass, which increases the efficiency in the transportation sector and reduces biomass consumption compared to the usage of biofuels. For the case of the SEE the consumption of biomass (726 PJ) is just under its sustainable potential (726.74 PJ). This is an important improvement compared to the previous work in which 1670 PJ of biomass consumption was assumed for the same region [34].

Sensitivity analysis showed that the system could face with unsustainable use of biomass on extremely dry year. However, this should be covered by 'savings' in biomass during the wet years. Nevertheless, this leads to the conclusion that an emphasis should be put on climate modelling in the future research.

Finally, although it is shown that it is possible, many serious steps, coordinated on a large scale, have to be made in order to gradually switch the SEE energy system from fossil dependent one to 100% renewable one.

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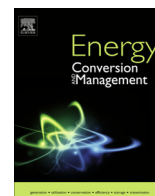
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Paper 2 - Economic feasibility of CHP facilities fueled by biomass from unused agriculture land: Case of Croatia

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Economic feasibility of CHP facilities fueled by biomass from unused agriculture land: Case of Croatia



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ABSTRACT

In this paper, the energy potential of biomass from growing short rotation coppice on unused agricultural land in the Republic of Croatia is used to investigate the feasibility of Combined Heat and Power (CHP) facilities fueled by such biomass. Large areas of agricultural land that remain unused for food crops, represent significant potential for growing biomass that could be used for energy. This biomass could be used to supply power plants of up to 15 MW_e in accordance with heat demands of the chosen locations. The methodology for regional energy potential assessment was elaborated in previous work and is now used to investigate the conditions in which such energy facilities could be feasible. The overall potential of biomass from short rotation coppice cultivated on unused agricultural land in the scenarios with 30% of the area is up to 10 PJ/year. The added value of fruit trees pruning biomass represents an incentive for the development of fruit production on such agricultural land. Sensitivity analysis was conducted for several parameters: cost of biomass, investment costs in CHP systems and combined change in biomass and technology cost.

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1. Introduction

In the European Union's (EU) struggle to achieve the energy package goals in 2020, in particular increasing the share of the EU energy consumption produced from renewable resources to 20%, biomass has a very significant position with 68% share of total gross inland consumption of renewable energy in 2011 and 8.4% of total final energy consumption in Europe in 2011. At the same time biomass is almost exclusive renewable fuel for heat with 95.5% share [1]. In Croatia, besides being widely used for domestic heating in rural areas, biomass is a dominant renewable resource in the most recent National Renewable Energy Action Plan, with a planned contribution of 26 PJ and 85 MW of capacity in 2020 [2]. These ambitious goals rest on biomass due to its socio-economic potential in Croatia, which is higher compared to the other renewable resources because of Croatia's forest and land potential. Croatia has problems with unemployment, similarly to some other countries in the EU, and at the same time large areas of unused agricultural land, both in public and private sectors. Extensive

research has been conducted so far on the marginal land use for growing crops for biomass and biofuels [3]. Today, overall agricultural land in Croatia amounts to 2,955,728 ha. Out of that, 1,074,159 ha is considered suitable, 1,074,510 ha is considered to be of limited suitability and 806,328 ha is listed as unsuitable for agricultural production [4]. In order to fulfil its goals regarding renewable energy sources integration, while making a change and progress in other mentioned fields, Croatia might resort to Short Rotation Coppice (SRC), a form of cellulose biomass that has already been developed for energy use in some other countries of the EU. Previous research in this field in EU countries focused on annual yields [5] and most favorable species [6], and impact on soil [7] and biodiversity [8]. These energy crops are eligible for cultivation on a wide range of soils that are of limited suitability or unsuitable for agricultural production. Initial studies have already been carried out in the field of choosing the optimal clones of willow and poplar. These species are common in Croatia and thus most relevant candidates for use on larger scale, as shown for white willow [9], with respect to the issue of marginal land [10] and to the way appropriate clones of willow are chosen [11]. Moreover, initial research has been carried out to frame the overall potential of marginal land on the whole territory of Croatia [12]. Although there are some experimental fields of willow being

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studied, there is no commercial SRC farm currently in Croatia. Recent study discussed the uptake of the SRC by the farmers in Europe [13], which demonstrated that the potential profitability of SRC is not yet recognized, while the study of economics of SRC in continental Europe gives the roadmap toward the increase in feasibility compared to other types of crops [14].

The usage of SRC, as well as other energy crops started in Scandinavian countries right after the oil crisis in the 1970s. Production chains with energy crops are well developed in Sweden, Finland, the UK and Denmark and are making progress in countries of Central and South Europe. Recent data on areas under various energy crops is given in Table 1.

Important part of energy transition toward systems based on renewable energy sources is district heating with combined heat and power (CHP) plants using biomass as the energy source. Because of their importance, a lot of research has been conducted recently to investigate the application of these types of solutions. In [15] results for three variants of combined heat and power (CHP) biomass plants were calculated. Kilkis [16] developed a model for the net-zero exergy district development for a city in Sweden, which among other units includes a CHP plant with district heating and cooling system. Krajačić et al. [17] provided an overview of potential feed-in tariffs for different energy storage technologies. Wang et al. [18] published a paper dealing with multi-objective optimization of a combined cooling, heating and power system driven by solar energy. Raine et al. [19] optimized combined heat and power production for buildings using heat storage. Mikulandrić et al. [20] examined the possibilities of a hybrid District Heating (DH) systems in small towns, with advantages in lower cost when the system is powered by renewable energy. Recently, the study of biomass CHP and DH applications in the urban areas being competitive with natural gas was conducted in Pantaleo et al. [21], with detailed sensitivity analysis conducted in a separate paper [22]. In Rudra et al. [23], the research goes further to propose more complex novel polygeneration systems based on biomass utilization, which increases the efficiency of resource utilization, minimizes the impact on the environment due to distributed generation and, through flexible operation, supports the integration of renewable energy [23]. Research in the use of biomass for CHP systems is well connected to the overall goal to achieve energy systems with 100% energy produced from the renewable sources. In the recent research regarding the possibility of 100% renewable energy system in the whole SEE, biomass is viewed more conservatively than before, with the energy potential of 726 PJ/year for the entire region. The use of SRC could increase this potential further [24].

In this paper, the research builds upon the current state-of-the-art scientific work by showing how unused agriculture land in Croatia could be used to cultivate SRC, which later could be used as fuel in the CHP plants. This is considered firstly for a novel system that combines cooling, heating and power and is supplied by storage. Further elaboration is conducted regarding feasibility of such system and the sensitivity analysis of the most important factors.

2. Metodology

Short rotation coppice species are perennial species which have a lifetime of 15–20 years, depending on the species, and are usually harvested every 2–8 years. In order to have continuous output of biomass for energy plants each hectare of agricultural land deemed to be at the disposal is divided into three fields, with the assumption that in every rotation only one field would be harvested, so that one hectare supplies biomass continuously during the lifetime

Table 1
Cellulosic energy crops in EU in 2011 [1].

	Willow (ha)	Poplar (ha)	Miscanthus (ha)
AT	220–1100	880–1100	800
BE	60		120
DK	5697	2807	64
FR	2300		2000–3000
DE	4000	5000	2000
IE	930		2200
IT	670	5490	50–100
LT	550		
PL	5000–9000	300	
SE	11,000	550	450
UK	1500–2300		10,000–11,000

of the species [25]. Therefore, the technical potential of the respective county or region is calculated in Eq. (1):

$$\sum_{i=1}^n B_{teh}(i) = \sum_{i=1}^n (A(i) * P_y(i) * k + A_f(i) * P_f(i)) \quad (1)$$

where $B_{teh}(i)$ is the technical potential of the county (i) (t), $A(i)$ is the area of unused agricultural land at the disposal (ha), $P_y(i)$ is the yearly production of biomass from the species used on the area A in (t/year) and k is the factor of rotation which determines the pace of harvesting. For every species or clones, factor k can be arbitrated according to the location in question. Furthermore, $A_f(i)$ is the area of the county (i) under fruit trees (ha) and $P_f(i)$ is the yearly production of biomass from pruning of the fruit trees (t/year).

The energy potential of the respective county or region is calculated with the assumption that the obtained biomass is stored after harvesting and finally reaches the gate of energy plant with moisture value of 30% and lower heating value of 3.5 kW h/kg respectively [26]. The energy potential is calculated in Eq. (2):

$$B_{ep}(i) = B_{teh(i,SRC)} * Hd_{SRC} + B_{teh(i,fruit)} * Hd_{fruit} \quad (2)$$

where $B_{ep}(i)$ is the energy potential (GJ/year) of the county (i) and Hd_{SRC} is the lower heating value of the biomass from SRC at the gate of energy plant (GJ/t), while $B_{teh(i,fruit)}$ is the technical potential of biomass from fruit trees pruning (t/year), $B_{teh(i,SRC)}$ is the technical potential of biomass from SRC (t/year) and Hd_{fruit} is the average lower heating value of biomass from fruit trees pruning (GJ/t).

For the calculation of the price of biomass at the gate of power plant, the method from [27] was used in Eq. (3). The price of biomass as a function of the SRC farm distance from the power plant is calculated:

$$C_{B,E} = \sum_{i=1}^n \frac{[C_B + (T_p \times U_i)] \times K_{Bi}}{P_B} \quad (3)$$

where $C_{B,E}$ is the price of biomass at the gate of power plant (€/t), C_B is the price of biomass harvested from the SRC farm (€/t), T_p is the specific cost of transport (€/t/km), U_i is the average distance between the farm and power plant (km), K_{Bi} is the amount of biomass from the location (i) (t), P_B is the total yearly amount of biomass used by the power plant (t).

For the purpose of gaining a better insight into regional differences in potential, which is crucial for economic viable choice of location for both SRC farms and biomass power plants, the scenario approach has been adopted. Various percentages of unused agricultural areas have been taken into account and the difference between public and private agricultural land has been considered in order to benefit the future research of different operational and maintenance costs of SRC farms. The farms can be run by hired workforce and mechanisation compared to private landowners that can use their own, slightly modified mechanisation and labor, which might lower the costs significantly.

The cost of the biomass harvested from the SRC farm is calculated according to Eq. (4) [12,25]:

$$C_B = T_S + T_Z + T_{O\&M} \quad (4)$$

where T_S is the cost of seeding material (€/ha), T_Z is the cost of land cultivation and $T_{O\&M}$ is the cost of labor and harvesting in the life cycle of species. Typical costs in Europe are shown in Table 2. The selling price is expressed in Euro per ton of dry matter (DM).

In each scenario, a combination of SRC, predominantly willow and fruit cultures, will be considered for the production of biomass. For the calculation of biomass costs at the respective power plants' gate and the Net Present Value (NPV) for each location, a code programmed in MATLAB has been used. It is an original code from [25], altered in order to take into account unused agricultural land instead of forests and forest residue. The model develops a network of quadrants with each quadrant representing an area of 1 km². The model calculates the average price per tonne of biomass ($C_{B,E}$) in each quadrant, and selects the most appropriate site. The code firstly positions in a particular quadrant and then calculates the amount of biomass resources which are sorted according to the distance. Biomass being closer has an advantage over the more distant biomass until it reaches the last source of biomass to be taken. For the most favorable location it lists the correct order of the sources, which it takes the biomass from with the amount of biomass taken from each source. Due to the simple assignment of input data, a piece of code that selects the waste biomass from wood processing industry can be easily modified if there is another potential source of biomass, such as agricultural land planted with SRC. All locations are given in the form of geographical coordinates: latitude and longitude. Distances between specific coordinates of the model are calculated using the Haversine formula, which takes the Earth as a sphere, ignoring the effects of the ellipse.

The Haversine formula has been first used in the beginning of the 19th century. The formula calculates the distances between the two points on a sphere using the spherical triangles. Thus, simplifying the Earth's shape as a sphere instead of an ellipsoid, the Haversine formula can be used. Due to the relatively short distances between different areas in the model, this simplification doesn't influence the result significantly since the mistake never goes beyond 0.5% [28].

3. Case study Croatia

Macro-locations for power plants have been chosen according to local heat demands obtained from the Sustainable Energy Action Plans (SEAP) of the cities considered. In each location that was considered, heat demand was taken from the SEAP and used as a base for calculation of the required CHP installed capacity, which was 15 MW_e and 30 MW_t for each location being investigated.

Since there are no commercial SRC farms in Croatia so far, the price of biomass from such a farm was calculated including the establishment of the farm, yearly expenses for workforce and mechanisation and yearly production of biomass from the hectare of area, taking into consideration various soil quality and suitability. Investment, operation and maintenance costs were estimated to be 6267 €/ha for the whole life cycle of 12 years of willow cultivation, achieving 12 t_{DM}/ha/year or 144 t_{DM}/ha in the life cycle of the SRC farm. Therefore, C_B of biomass from such a farm was estimated to be 43.47 €/t [12]. In the case of willow, a 3-year rotation has been selected for the calculation. Using state owned land (through land concession or other instruments) is beneficial from the point of view of ownership, which is often a great barrier for any area intensive project in Croatia, since private land is often shared by multiple owners. On the other hand, at locations where

Table 2
Typical costs for SRC farms [12,30].

Location	Species	Cultivation costs (€/ha)	Operation costs (€/ha/y)	Selling price (€/t _{DM})
Sweden – Nynas Gard	Willow	1222	330	65
Sweden – Puckgarden	Willow	1110	265	52
Latvia	Willow	1450	n/a	n/a
Latvia – Salixenergi	Willow	1630	480	n/a
France– Bretagne	Willow	2545	355	n/a
Germany – Goettingen	Poplar	2750	250	65
Italy – Rinnova	Poplar	2320	875	55
Croatia	Willow	3916	196	43.47

private land could be utilized without a very costly and time consuming process of dealing with ownership problems, the costs of land and mechanisation could be lower, presenting the investors with the opportunity to reach the scenarios presented in sensitivity analysis, making the SRC production feasible.

In order to make comparison, as well as to preserve biodiversity and encourage production in the region, biomass from fruit trees pruning was also taken into account in the scenarios. The amount of biomass from fruit trees was calculated according to [29]. Table 3 reports on how much biomass could be obtained by pruning of plantations of respective fruit cultures. The combustion of other types of biomass with biomass from SRC is considered desirable at this stage in the practice of Central European countries [30].

The separate issue is the statistical coverage of unused agricultural land. It has been followed through yearbooks of the National Bureau of Statistics until the year 2005, when due to the adjustment to the European standards in statistics, unused land was no longer published as a dataset. In the year 2009, a new Agency for Agricultural Land was founded and started to review data on state-owned agricultural land.

Their newest findings were used here to calculate available agricultural land in each county. For private unused agricultural land, data from the Statistical Yearbook 2004 of the National Bureau of Statistics was used. Although the difference of 10 years in datasets could cause some inaccuracies, assumptions in the scenarios were conservative enough to make sure that the calculated technical potential could be actually achieved [31]. In Table 4 the data on unused agricultural land is provided [32].

Private land stands for exclusively private-owned land, while the state-owned land is in the ownership of local self-government or the companies such as the Croatian Forests, owned directly by the country of Croatia. The difference is significant due to the state of the land, concerning the ownership by private citizens, which usually makes the land on the same location more fragmented and causes significant practical difficulties for anyone trying to put the land into use.

For the case study of Croatia, scenarios were devised as follows:

SCENARIO 1 – 30% of unused agricultural land was used to cultivate willow SRC. The scenario was divided according to the ownership to show the difference in local potential when:

- (1a) 30% of state-owned land was used
- (1b) 30% of private land was used
- (1c) 30% of aggregated state-owned and private land was used

SCENARIO 2 – 20% of unused agricultural land was used to cultivate willow SRC. The scenario was divided according to the ownership to show the difference in local potential when:

- (2a) 20% of state-owned land was used
- (2b) 20% of private land was used
- (2c) 20% of aggregated state-owned and private land was used

Table 3
Biomass from fruit trees pruning [29].

	Total biomass (kg/ha)
<i>Fruit trees</i>	
Apple	5571.43
Pear	5833.33
Peach and nectarine	2921.21
Apricot	1619.58
Cherry (sweet and sour)	1783.07
Plum	2053.15
Fig	1281.12
<i>Dry fruit trees</i>	
Walnut	538.04
Hazelnut	1848.48
Almond	1625.17
<i>Grape</i>	
Total	4258.37
<i>Olive</i>	
Total	2522.22

Table 4
Unused agricultural land divided according to ownership [25,32].

County	Public (ha)	Private (ha)
Krapina-Zagorje	115.27	1783
Varazdin	1009.79	1469
Međimurje	1702.89	2910
Koprivnica-Križevci	2563.36	987
Osijek-Baranja	3826.71	5316
Vukovar-Srijem	4445.69	2662
Virovitica-Podravina	7019.16	5221
Zagreb	7989.94	8890
Bjelovar-Bilogora	9974.94	15,476
Požega-Slavonia	15,391.35	12,875
Brod-Posavina	19,689.77	7326
Karlovac	32,767.84	82,259
Sisak-Moslavina	33,733.16	57,412

SCENARIO 3 – 10% of unused agricultural land was used to cultivate willow SRC. The scenario was divided according to the ownership to show the difference in local potential when:

- (3a) 10% of state-owned land was used
- (3b) 10% of private land was used
- (3c) 10% of aggregated state-owned and private land was used

SCENARIO 4 – 20% of unused agricultural land was used to combine cultivation of willow SRC with the increase in production of the most widespread fruit sorts in Croatia (apple, pear, peach, cherry, plum, walnut and hazelnut) according to the data from [33]. The scenario was divided according to the ownership to show the difference in local potential when:

- (4a) 20% of aggregated state-owned and private land was used, divided to achieve a 100% increase in areas under most widespread fruit sorts and to use the rest of the area for SRC cultivation.
- (4b) Same as in 4a, but with a goal to achieve a 50% increase in areas under fruit sorts.
- (4c) Same as in 4b, but with a goal to achieve a 25% increase in areas under fruit sorts.

District heating systems powered by the acquired biomass ran on novel Combined Heat and Power (CHP) plant, in order to meet as much energy demand as possible. For this case study, data from Table 4 was calculated as the base data of the CHP plant. The District Heating System (DHS) includes heating grid and heat storage

to allow the plant to extend its availability during months with lower heat demand and to enable peak shaving.

Recently, following the European Commission's recommendation, a new form of subsidizing the investment in renewable energy sources has been implemented in Croatia. Instead of feed-in tariffs used before, a feed-in premium has been approved to be the main scheme for subsidizing renewables [34]. It is expected that a tender will be called for filling in the quotas set for specific technology in which the offer with the lowest feed-in premium will be chosen. However, as the procedure is only in the starting phase, the range of offers that will be offered is still unclear. Thus, the best approximation can be found in Dominković et al. [35]. The calculated feed-in premium should be around 0.085 €/kW h of electricity supplied to the grid in order that subsidy level remains in the same range as it was the case with feed-in tariffs. For this case study, the level of subsidy is given in Table 5.

In Fig. 1, the simulated behavior of the CHP plant on the market is given. The blue¹ line is the income from the market, according to the Nordpool market prices from 2014, and the red line is the income including the Feed-in Premium.

Since the new Act is not yet in force and no ordinances have been declared to describe how the feed-in premium will be implemented, the sensitivity analysis is conducted under the Act that is still in force and uses a feed-in tariff, calculated on the basis of the average, “blue” tariff from [36].

4. Results

In this section, the results of the methodology applied in the case study of Croatia are presented. Also, the sensitivity analysis is performed at the end of the chapter to discuss the circumstances in which the exploitation of this potential for fuel in CHP could be feasible.

Technical potential and energy potential of biomass from SRC for the scenarios 1a, 1b, 2a, 2b, 3a and 3b for six most promising counties are shown in Fig. 2.

There is a noticeable potential in the Karlovac and Sisak-Moslavina counties due to the large areas of unused agricultural land in those counties. This can be seen in even greater disparity in Fig. 3, which shows the results of technical and energy potential of biomass from SRC for the scenarios 1c, 2c and 3c.

In the scenarios 4a, 4b and 4c shown in Fig. 4, technical and energy potential are lower due to the inclusion of the biomass from fruit trees pruning. However, the advantages of that are larger employment and the reduction of country's fruit import dependence.

Technical and energy potential for all the scenarios for the Continental Croatia (counties from Table 4), is given in Table 6. Counties of the Mediterranean Croatia were not included in this paper because of specific differences in climate and soil, which would influence the choice of SRC culture that should be cultivated. Moreover, the scarcity of agricultural land in those counties might contribute to seeing SRC as a competition with food crops. For the economic feasibility of such power plant and its DHS, the method of the Net Present Value (NPV) was used. Negative results for each of the macro-locations are presented in Fig. 5, which shows nets of 19 × 19 km of each macro-location for the scenario 1c. The values presented in Fig. 5 show that this value chain, connecting SRC and CHP with seasonal storage would not be feasible with the given parameters.

Using the code in Matlab from [35], the techno-economic analysis was conducted for macro-locations in Croatia. Results

¹ For interpretation of color in Fig. 1, the reader is referred to the web version of this article.

Table 5

Base data for the calculation of the CHP plant [37–39].

	Amount	Unit
Power plant availability	0.9	
Biomass price at the SRC field	43.47	€/ton
Lower calorific value (30% moisture)	3,500	kW h/ton
η power plant total	0.87	
η_{el}	0.29	
HTP ratio	2.00	
η storage	0.8	
Storage temperature	90	°C
Power plant specific investment cost	3600	€/kW _e
Absorber investment cost	400	€/kW
District system piping cost	5820	€/dwelling
Dwellings connected to DHS	8700	
Storage investment cost	56	€/m ³
Plant's own electricity consumption	6%	
Discount rate	7%	
Feed-in-tariff	0.122	€/kW h _e
COP	0.7	
Design temperature for heating	21	°C
Design temperature for cooling	26	°C
Fixed power plant O&M cost	29	€/kW per annum
Variable power plant O&M cost	0.0039	€/kW h
District heating O&M cost	75	€/dwelling per annum
Storage O&M cost	0.39	€/m ³ per annum
Heating energy revenue	0.0198	€/kW h
Project lifetime	14	Years

are supplied in a view of the cost of biomass at CHP plant's location – which was optimized according to this cost.

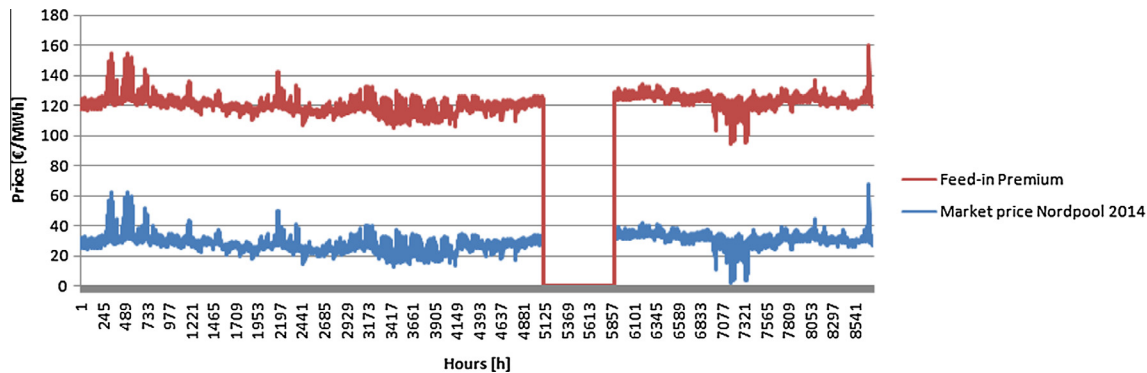
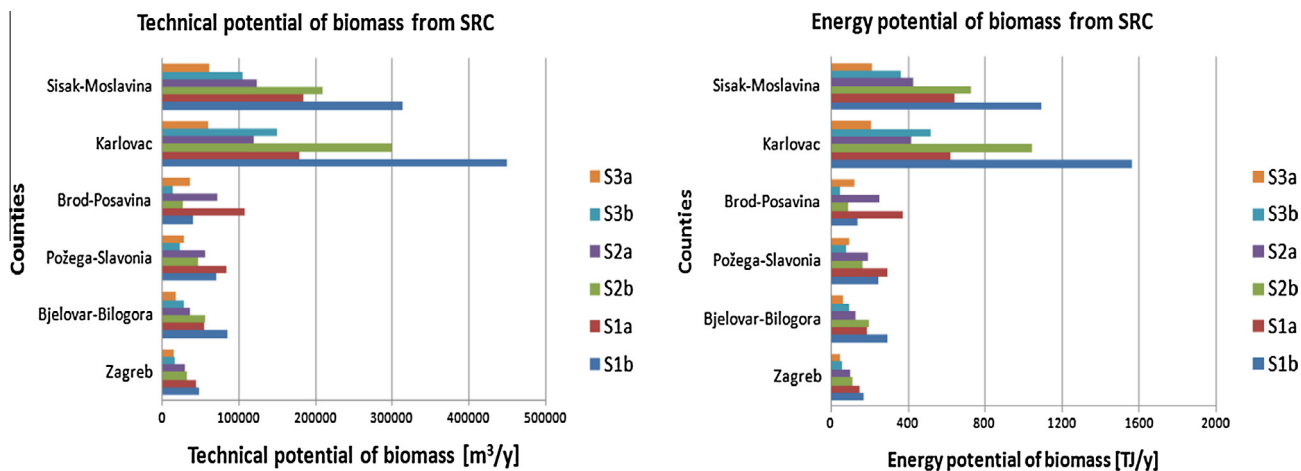
In order to supply complete information, the cost of biomass for each scenario and location is presented in Table 7. Locations in the vicinity of the Karlovac and Sisak-Moslavina counties have lower prices of biomass from SRC.

Other factors that are challenging for the implementation of SRC biomass based DHS are the size of the heating (cooling) network and the cost of SRC biomass. The cost of the biomass could be influenced in particular by encouraging private landowners to adopt SRC cultivation and use their own mechanization and workforce. In Fig. 6 the result of sensitivity analysis is presented.

The sensitivity analysis was performed for the case of Osijek macro-location because of the least amount of available land for the SRC cultivation in the surrounding counties. Furthermore, this location already has a DHS grid, which is the first criteria that would need to be fulfilled at this point, if the use of SRC is to be feasible.

The factors discussed in the analysis are investment cost, the price of biomass following investment cost changes and the price of biomass without the change of the investment cost.

Therefore, when discussing the lower price of biomass stand-alone, it refers to only taking into account the lower price of biomass without change of the investment cost or other conditions. When discussing the reduced investment cost, the price of biomass

**Fig. 1.** Model of feed-in premium in market conditions for the CHP plant [35].**Fig. 2.** Technical and energy potential of biomass from SRC in "a" and "b" scenarios.

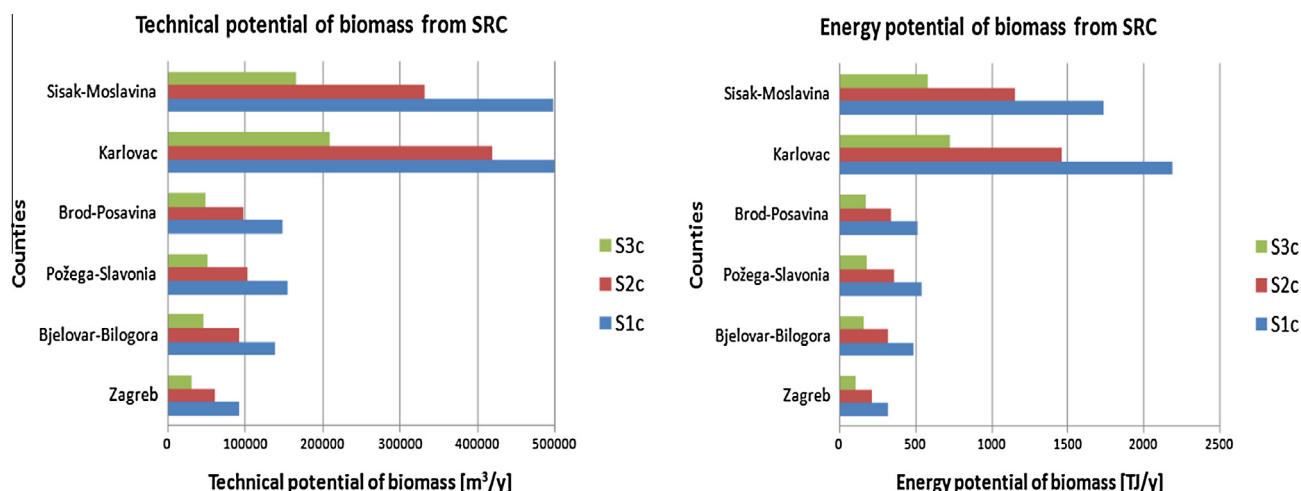


Fig. 3. Technical and energy potential of biomass from SRC in aggregate land scenarios.

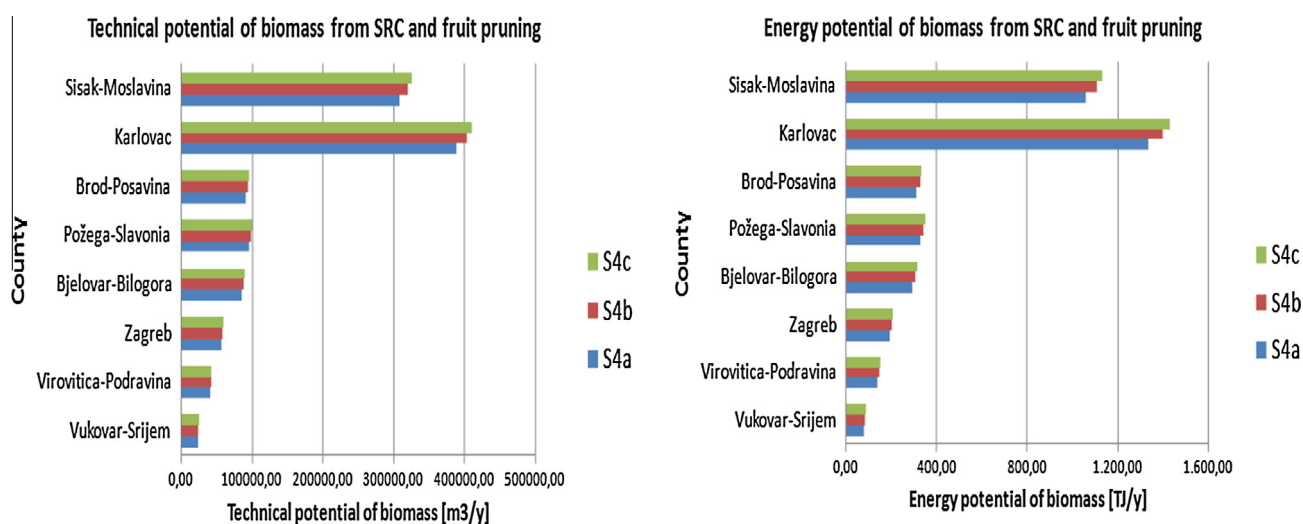


Fig. 4. Technical and energy potential of biomass from SRC and fruit trees pruning.

remains constant, while the combined approach takes into account both effects: investment cost reduction and reduction in the price of biomass at the same time.

It can be seen that only the simultaneous reductions of the investment cost and the price of biomass made the system economically feasible. Large difference toward feasibility is expected and can be reached in reality through incentives or by choosing simpler systems like the already working DH systems with the fuel shift to SRC. Price of the SRC and fruit biomass can be lower if the rate of privately owned land is increased, and the price of fruit pruning biomass decreased. The biomass price can be further lowered by using one's own labor force in a combination with entrepreneurs who own their machinery.

5. Conclusion

Cultivating SRC for biomass has already been commercially established value chain in some of the EU countries, especially in Sweden, Denmark, Germany, the UK, Poland and Italy. In the EU, research continues on the influence of SRC on soil, SRC yield and the best practices to exploit SRC for biomass as a valuable contribution to common energy and environmental goals in 2020 and

Table 6

Technical and energy potential for aggregated for continental Croatia.

Croatia	Technical potential (m ³ /y)	Energy potential (TJ/y)
S1 _a	1,404,094	4902
S1 _b	1,426,108	4979
S1 _c	2,830,202	9881
S2 _a	936,062	3268
S2 _b	950,738	3319
S2 _c	1,886,801	6588
S3 _a	468,031	1634
S3 _b	475,369	1659
S3 _c	943,400	3293
S4 _a	1,169,257	4176
S4 _b	1,212,193	4329
S4 _c	1,233,661	4356

beyond. In Croatia, SRC can be seen as a new fuel, which fosters the integration of factors such as large areas of unused agricultural land, high unemployment and renewable sources inclusion goals. Analysis of regional potential shows that even conservative assumptions on the area that could be cultivated with SRC could lead to the substantial contribution to meeting local energy demands in a more sustainable way and creating new job opportunities at the same time. At the moment, the most innovative

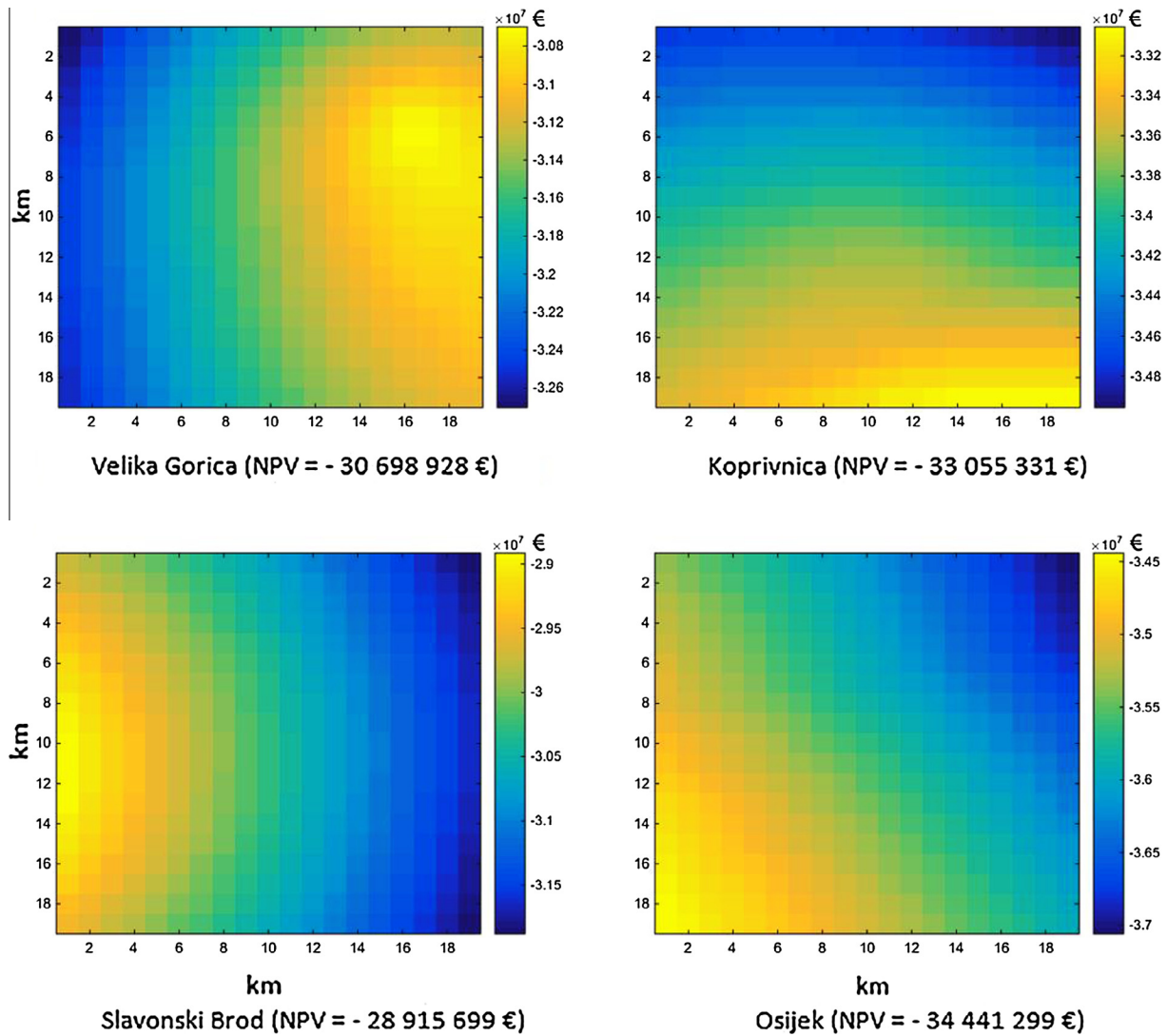


Fig. 5. NPV of optimal locations at each macro-location for the scenario S1c.

Table 7
Cost of biomass at plant location from all scenarios.

Location	Velika Gorica	Koprivnica	Slavonski Brod	Osijek
Scenario	Cost $C_{B,E}$ (€/t)			
S1a	47.7	51.1	45.9	51.9
S1b	47.6	50.2	48.7	52.3
S1c	46.4	48.7	44.7	50.0
S2a	48.2	52.6	47.7	52.9
S2b	48.0	51.8	51.2	55.0
S2c	47.4	49.7	46.2	51.2
S3a	50.7	55.2	53.3	58.9
S3b	49.3	53.8	55.7	61.2
S3c	48.0	52.2	49.2	53.4
S4a	47.5	49.9	46.4	51.5
S4b	47.4	49.8	46.3	51.3
S4c	47.4	49.7	46.3	51.3

approaches with the combined heating and cooling plants with seasonal storage are not the economically feasible way of exploiting biomass from SRC, but some more conventional CHP solutions would be feasible to implement.

Further research should be conducted on more precise determination of the unused agricultural areas which could be used for the SRC cultivation. This could lead to the creation of local value chains

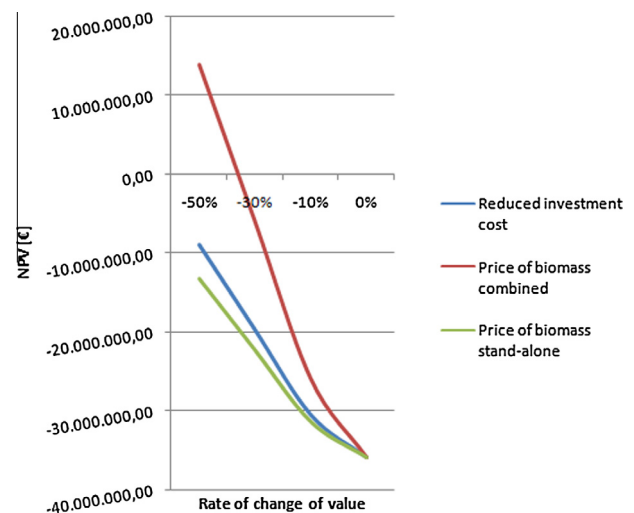


Fig. 6. Sensitivity analysis in relation to investment cost and price of biomass.

which would include SRC and other biomass sources to meet local demand in a sustainable way through DHS. Other important reductions of cost could be achieved by the use of private landowners'

own machinery and workforce, which could make the SRC biomass more competitive and interesting for further investigation.

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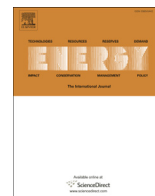
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Paper 3 - Waste to energy plant operation under the influence of market and legislation conditioned changes

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Waste to energy plant operation under the influence of market and legislation conditioned changes



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ABSTRACT

In this paper, gate-fee changes of the waste-to-energy plants are investigated in the conditions set by European Union legislation and by the introduction of the new heat market. Waste management and sustainable energy supply are core issues of sustainable development of regions, especially urban areas. These two energy flows logically come together in the combined heat and power facility by waste incineration. However, the implementation of new legislation influences quantity and quality of municipal waste and operation of waste-to-energy systems. Once the legislation requirements are met, waste-to-energy plants need to be adapted to market operation. This influence is tracked by the gate-fee volatility. The operation of the waste-to-energy plant on electricity markets is simulated by using EnergyPLAN and heat market is simulated in Matlab, based on hourly marginal costs. The results have shown that the fuel switch reduced gate-fee and made the facility economically viable again. In the second case, the operation of the waste-to-energy plant on day-ahead electricity and heat market is analysed. It is shown that introducing heat market increased needed gate-fee on the yearly level over the expected levels. Therefore, it can be concluded that the proposed approach can make projects of otherwise questionable feasibility more attractive.

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1. Introduction

A large generation of waste per capita, out of which over a quarter is Municipal Solid Waste (MSW), classifies waste management (WM) as one of the core issues in sustainable development of EU regions. This problem is even more emphasized in urban and metropolitan areas with higher population density. With increasing population, energy consumption also increases. For that reason, urban energy systems have been analysed in many previous research papers. Urban solutions for district heating (DH), the data, and technologies, have been recently discussed in Ref. [1]. For such urban applications, optimal planning methods have been elaborated in Ref. [2], with the case of Russia. Relevant is also the study of the integration of high share of renewable energy sources [3],

which stipulated that energy-only markets need to be addressed for the correct price signals and the flexible measures are of the key relevance for the high RES integration. In this context, flexible WtE CHP plant is a relevant factor in two energy markets: electricity and heat market. Therefore, integration of waste and energy systems represents the logical path in the sustainable development of regions. The importance of the usage of local energy sources in local energy systems, as well as their positive influence on the overall EU energy system, is emphasized in Heat Roadmap Europe [4], [5]. In this study, waste was classified as one of the primary heat sources in district heating systems (DHS). While waste and its energy recovery may seem as an ideal energy source for usage in urban areas, EU has identified the material potential of waste, which can be utilized through its material recovery. The first step in this direction was taken by Waste Framework Directive [6] which sets waste hierarchy by which primary step for recovery of produced waste is recycling (material recovery), while energy recovery is subordinated to it. A step further in the direction of material recovery was made by the Circular Economy Package [7] which defines more

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rigorous goals by increasing the share of MSW, which needs to be primarily separated and prepared for material recovery. These legislative changes have a great influence on waste quantities that are available for usage in waste-to-energy (WtE) based systems [8]. These changes in WMS can put feasibility of incineration-based WtE systems in question as burnable waste quantity decreases. This problem can be compensated by the introduction of new fuels such as biomass. Woody biomass, agricultural and forest residue [9], as well as biomass from short rotation coppice grown on unused agricultural land [10], showed great potential for use in energy systems and sustainability. Efficient use of locally available biomass was analysed in Ref. [11].

The use of biomass in WtE DH plant has proven to be a viable practice, as well as in co-combustion regime and as the use of mixed wastes (MW) for base load and biomass for peak load coverage [12], but time changes in waste quantity are not tracked. Use of WtE in conjunction with energy storage in variable electricity pricing environment, on industry scale, has been analysed and proven to justify a higher establishment cost of WtE [13].

During the lifetime of the WtE DH projects, a “business as usual” way of planning the waste incineration implies a constant increase of MSW quantity with a uniform quality. This is connected with increasing waste generation due to the growth of population and standard of living. This trend was already described by Kuznets curve hypothesis (EKC) which claims that economy growth (that can be defined by income per capita) has a negative impact on environment to a certain point after which environmental impact is reducing. This hypothesis was also adapted to MSW and called waste Kuznets curve hypothesis (WKC) and proved that household MSW generation per capita income also follows this correlation [14]. Also, this threshold was already reached by one part of the households/provinces in Japan [14] and Italy [15]. This trend shows that solving waste problem by building new waste disposal facilities can become unviable because increasing tendency in the MSW generation will come to an end. Furthermore, waste policies and instruments that encourage waste prevention can further decrease waste generation [15]. In the EU, the absolute decoupling trend is not present, but the elasticity of waste generation to income drivers is lower than in the past which indicates relative decoupling [16]. Also, current policies do not provide incentives for waste prevention, which will have to change. The introduction of new WM solutions, oriented to the reduction of waste production, re-using and recycling, reduces the amount of waste that needs to be disposed of [17]. The latter effect increases with time and can be viewed as a hazard for the feasibility of WM projects [8]. These effects are emphasized in new EU member states which have to quickly implement new WMS to achieve EU legislation goals but these systems also need to be economically sustainable. This should be done without drastically increasing the price of waste collection for the general population, as it would undermine waste collection system and cause problems such as illegal waste dumping. Therefore, the system needs to be designed to restrict volatility of gate-fees for waste treatment.

Reviewed literature did not sufficiently analyse time change of waste quantity and composition under the influence of WMS changes and its impact on WtE plants. Moreover, only in one paper [8] different ways of compensation of reduced waste quantities are analysed but the influence of secondary separation of waste was not considered. Furthermore, in Refs. [8] and [18] economic analysis of the operation of waste incinerators was considered, but their overall efficiency is rather low because of the emphasis on electricity generation. Also, in these papers the influence of gate-fee change was analysed only through arbitrary sensitivity analysis without consideration of the influence of other parameters on gate-fee value. Papers that analysed co-combustion of biomass with

other fuels such as [19] did not deliberate big involuntary fuel substitution to sustain economic viability. The contribution of this work can be found in viability analysis of this possibility. In another part of this work, the focus was given to the market operation of considered facility. The influence which electricity grid tariffs have on flexible power to heat application was investigated in Ref. [20], but more research was done in the field of the possibility of plants operation on the open electricity market [21], [22]. As for the heat energy market, it is still in its infancy as most of the DHS are in public/municipality ownership. However, even in this segment, diversification of ownership is undergoing [23] which inevitably fosters the establishment of heat markets. Open DHS operation was already analysed [24] which consequently led to the analysis of waste incinerator operation on both energy markets in this paper. Upon the possible development of the dynamic heat market in Denmark, WtE plants could face the economic problems as they would not have guaranteed access to the DH market anymore. In addition, a local WtE plant can expect partial fuel switch in the foreseeable future due to a lack of economic feasibility of the waste import [25]. The contribution of this work can also be found in the economic analysis of dynamic WtE which operates on two markets. By introducing new fuel, WtE plant is already switching from operation in regulated conditions without third-party access which means a switch from stable fuel and energy prices to partially market defined fuel prices. On the other hand, after the transition to new WMS, WtE plants need to be ready to compete on open electricity and heat markets. By doing that, a care must be given to the gate-fee volatility, which is unavoidable in open market operations, while at the same time social-economic component of waste quantity and quality represents one more aggravating circumstance.

During the process of defining the case study, big difference in gate-fee values was observed across the EU – up to 176 €/t, calculated as a mean value with the addition of waste incineration tax [26]. Also, the difference in national legislations defines a wide range of tax values for different WM and disposal technologies. This is the result of the organization of the WM and its efficiency. Therefore, in this paper case studies of Croatia, where WMS does not meet EU criteria and has one of the lowest recycling rates, and Denmark, which has greatly exceeded the EU goals and is considered to be one of the most advanced systems that even makes extra income from the import and disposal of waste from neighbouring countries. This comparison extends the current knowledge by comparing the two extremes and leads to the conclusion that the investment in thermal waste treatment can be cost-effective in a wide range of configurations of WM system, without constituting an additional financial burden for the municipality or its citizens.

2. Methods

The influence of adaptation to new WM legislation on WtE plants is tracked by analysing gate-fee volatility. Also, a method for adapting to expected changes in fuel supply of only planned WtE plant in Croatia and its management is proposed. To compensate for reducing the amount of primary fuel (waste), the share of secondary fuel is gradually increased until the final fuel shift is achieved. Fuel substitution is guided by waste amount prognosis in the analysed time period. This trend is pronounced in all new EU countries, which in the next couple of years have to invest a great effort to implement primary separation into WMS. Changes in the waste collection are expected in order to achieve EU goals gradually, but they cannot solve the waste disposal problem completely, so other ways to tackle this problem are explored. Implementation of other technologies, such as Mechanical Biological Treatment (MBT), is expected to further reduce the quantity of waste available

for energy production.

To analyse these changes, production of MSW in the future years is needed to be forecasted. Future waste generation data were adapted from WM, literature or, where these data were not available, by usage of the LCA-IWM prognostic model [27]. In the novel model, the forecast of MSW waste generation and composition on the basis of actual data and a wide range of socio-economic data was taken into account. Also, legislation goals which define forecast boundaries were considered. Output data were structured as overall waste per fractions with and without MW fraction separately reported so all streams can be calculated as well as MW composition. The possibility of waste decoupling was not taken into account, as it was not expected and modelled in long-term projections. Changes expected due to intervention in the WMS were also tracked. LHV of waste were calculated by using the chemical composition of each waste fraction [28] through Mendeliev equation - Equation (1):

$$LHV = 4.187(81C + 300H - 26(O - S) - 6(9H + W)) \left[\frac{kJ}{kg} \right] \quad (1)$$

where C, H, O and S represents the share of corresponding chemical elements and W represents water share. The calculation of average LHV of mixed municipal waste is based on the calculated LHV of each fraction and physical composition of MW.

When existing WMS did not satisfy set goals, new WM scenarios were developed. The second scenario introduced MBT plant and is based on primary separation of waste, incineration, and MBT. All produced MSW, with the corresponding LHV, enters the incinerator only in the case of meeting legislation goals by source separation alone. Comparison of both scenarios for the case of legislation adaptation is shown in Fig. 1.

Process flow data for MBT plant, which is introduced in scenario With MBT were adapted from the literature data [29]. As shown in Fig. 2, MBT plant separates mainly bio-waste, metals, and glass, from the MW stream, which are prepared for material recovery processes. Another separated waste stream is Refuse-Derived Fuel (RDF) which is mainly composed of burnable fractions – paper and plastics, while the rest is unusable waste which is landfilled.

Waste components which are separated for material recovery do not contribute to the heating value of mixed MSW, so RDF stream's LHV is expected to increase. Quantity wise, this scenario further reduced available waste quantities for incineration and left space for introduction of second fuel.

To analyse the effect of legislation influenced waste reduction, as well as possible benefits from proposed compensation with secondary fuel, a gate-fee volatility analysis was conducted. The economic analysis was based on the case dependent conditions – national legislation as well as rules and regulations for system operation. The analysis tracked the minimum needed gate-fee to equalize annual cash flow to zero. This way of operation of municipal utility plants is logical because it is built with public

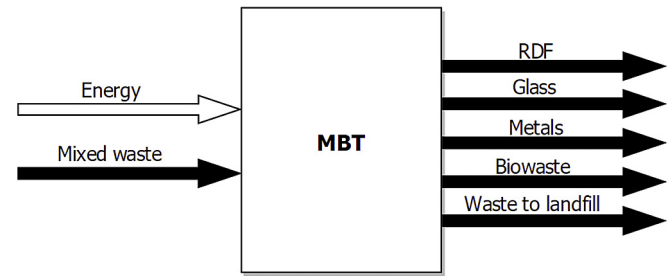


Fig. 2. MBT process flows data.

funds to provide public service, not to make a profit. The operation of municipal facilities without generating a profit is regulated in some countries by local or national legislation. Example for this is Denmark, where this is regulated at the national level.

For analysing volatility of gate-fee due to the operation on energy markets, the case of Denmark facility is chosen because nationwide adaptation to EU waste legislation has already been done. This analysis was performed to investigate the influence of operating the WtE plant on both, electricity and heat markets. To interpret results, two scenarios were constructed, the first one that analysed WtE plant operation on electricity market alone and a second one that analysed its operation on both markets.

In the first scenario analysis of WtE plant operation on only one energy market, i.e. the el-spot day ahead market, was carried out. In this case, the heat was assumed to be sold within the municipality under the regulated conditions, without the third-party access.

For the second scenario analysis, the operation of the plant on two markets was assumed, an electricity market and a district heat day-ahead market. This case study was carried out in order to assess the prospects of the operation of the WtE plant on the dynamic heat day-ahead market that would operate on a similar principle as the electricity day-ahead market. As the heat day-ahead market is non-existent in Sønderborg, its hourly demand-supply curve was simulated in Matlab, based on the heating production plants' hourly marginal costs. A similar approach was adopted for the simulation of the heat day-ahead market for the Espoo city in Finland [19].

Marginal price of plants was calculated using Equation (2):

$$MP = var_{O\&M} + fuel/\eta + tax_{fuel} - electricity_{income} - feed_in_{premium} \quad (2)$$

MP denotes marginal price of heat generation in each hour for each heat generation plant and has the unit [€/MWh_{heat}]. Variable operating and maintenance cost is denoted as $var_{O\&M}$, fuel cost and efficiency as $fuel$ and η , while tax_{fuel} denotes tax imposed on the use of fuels for energy generation purposes. CHP plants generate income from electricity sales on power el-spot day ahead market and

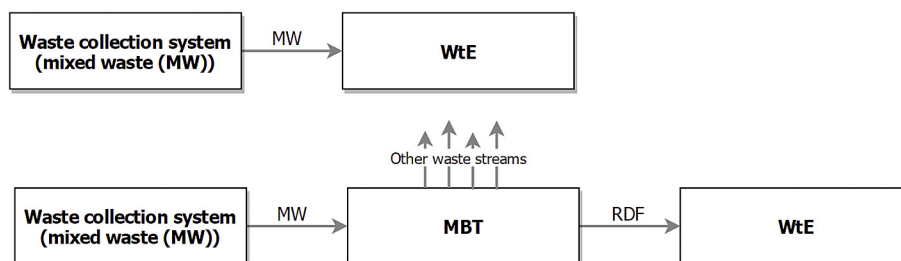


Fig. 1. Comparison of the scenarios Without MBT and With MBT.

this income is represented by the $electricity_{income}$ term while waste CHP plant is also eligible for feed-in premium which is represented by the $feed_in_{premium}$ term. The day ahead heat market was simulated using the case specific marginal heat generation costs of plants.

3. Case study

In order to investigate previously discussed changes in WMS and problems associated with them, the case study was created in which two cases were analysed: a potential project of incineration plant in Zagreb, Croatia, as the facility which is faced with upcoming challenges caused by harmonisation with EU waste legislation; and a case of the existing WtE plant in Sønderborg, Denmark, which is already operating on electricity market and faces the prospect of operating on both heat and electricity day ahead markets in the future.

3.1. Case of the Sønderborg municipality

The case of Sønderborg was used for market coupling analysis. Two scenarios were analysed – one based on the operation on electricity market (One energy market) and the second one, based on the operation on both electricity and heat markets (Two energy markets). DHS of the municipality of Sønderborg are well described in Ref. [30].

In Sønderborg municipality, approximately 160,000 tonnes of waste is collected every year out of which 45% is a household waste [31]. Waste is collected as separated waste streams and used for the production of electric and heat energy in incineration plant or used for material production, landfilled or processed in special treatment plants. In 2012, 74% of generated waste is collected for recycling. By municipal plans, these waste quantities are expected to grow as it is shown in Fig. 3.

Data for the years 2012, 2018 and 2024 were taken from existing plans [31], while 2030 data were obtained by linear extrapolation, as previous data showed linear time dependence. It was observed that waste quantities for all treatments are expected to increase.

Waste incineration CHP plant is a part of DH network in Sønderborg [32]. The plant is designed as combined cycle cogeneration plant with the conversion of waste energy in the steam cycle. Gas turbine waste heat is utilized for water pre-heating. It was designed to use 70% of natural gas and 30% of waste's energy but that ratio dropped to 0.3% for gas and 99.7% for waste in 2013. Also, the plant has achieved a gross efficiency of 90.5% in these new conditions and produced 160,148 MWh of heat and 36,069 MWh of

electricity from waste with average LHV of 11.2 MJ/kg. The amount of treated waste is 69,630 tonnes from which 33,258 tonnes is from Sønderborg municipality while the rest was imported from Aabenraa municipality and supplemented with waste imported from England and Germany up to the maximum capacity of the plant.

Because of the lack of its own waste to fully utilize WtE plants, Denmark has been steadily increasing its waste import from the UK. Sønderborg WtE plant also utilizes imported waste as one part of the full supply. In general, the Danish plant can expect a gate-fee between 27 and 40 €/t of waste (depending on the season and the quality of the waste), after the costs of transportation and different fees are taken into account [33]. The gate-fee for the waste collected in Denmark is 27 €/t and it is the lowest gate-fee in Europe [34], [35]. Current incineration tax is approximately 44 €/t and this rate was used for both case studies. On top of the gate-fee that the WtE plants receive, there is a feed-in premium of 0.01 €/kWh of electricity sold to the market [34].

In the first scenario, One energy market scenario, the case of Sønderborg WtE plant operating only on one energy market is analysed. The plant is operating on the el-spot day ahead market, while the heat was assumed to be sold within the municipality under the regulated conditions, without the third-party access. This case study represents the current operating scheme of the plant in Sønderborg, as well as the case for most of the DH operators in Denmark. WtE plants are owned by municipalities in Denmark, and they are not allowed to operate with profits; they can only recover their operating costs and investments [35]. Furthermore, the project time needs to be matched with the anticipated lifetime of the energy plant. For the latter reason, a project lifetime of 20 years has been assumed, based on the technical data available [36]. According to Energinet.dk's recommendation (Danish power and gas TSO), a real discount rate of 4% was adopted [37].

For the second scenario, Two energy markets scenario, a day-ahead heat market had to be established as no such market exists in the municipality of Sønderborg currently. It was simulated using the marginal heat generation costs of plants obtained from the figures presented in Table 1.

Gas is also taxed when used for energy production purposes at the rate of 27.7 €/MWh_{fuel} [38]. Average electricity price development on the el-spot market until 2030 was adopted from Ref. [37].

Recap of all the technical and economic data used for feasibility calculation of WtE plant in both cases is presented in Table 2.

As per [20] and [25], waste import after the year 2025 will not be economically viable anymore; hence, in this analysis the imported

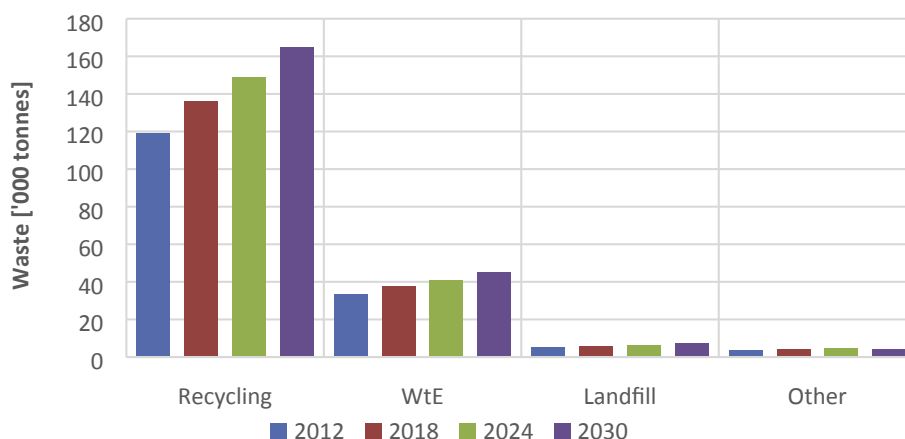


Fig. 3. Waste quantities per disposal technologies - Sønderborg.

Table 1

Costs used for establishing marginal heat price offers [36].

	Heat capacity [MW]	Electric capacity [MW]	η_e	η_{total}	Variable cost [€/MWh _{heat}]	Fuel cost [€/MWh _{fuel}]
Waste CHP ^a	20	4.5	0.18	0.98	4.2	–8.68
Gas CHP ^a	40	53	0.5	0.94	2.1	32.71
Gas boilers	100	–	0.96		5.4	32.71
Solar heating	6.1	–	1		1	0
Bio-oil	5.4	–	0.95		5.4	28.81
Geoth.+wood boiler ^b	12.5	–	1.35		5.4	28.81

^a Income from electricity sales on el-spot day-ahead market was subtracted from the heat marginal price offer on the day-ahead heat market. These values were different for each hour depending on the marginal electricity price. Hence, they are not represented in this table but they can be downloaded from www.nordpoolspot.com website, for the year 2015, DK-West area.

^b Geothermal heat coupled with absorption heat pump driven by biomass for heat generation. Modelled as biomass boiler with $\eta = 135\%$ as the geothermal heat was considered to be free.

Table 2

Technical and economic data of Sønderborg WtE plant [36].

WtE plant Sønderborg		
Capacity	4.5	MWe
	19.98	MW _{heat}
Total O&M	53	€/t
Investment cost	8,500,000	€/MW
Efficiency el	16.6%	
Efficiency total	90.5%	
Availability	92%	
Lifetime	20	years
Gate-fee	–27	€/ton
Incineration tax	44	€/ton
Feed-in premium	10	€/MWh
Real discount rate	4%	
Inflation	2%	

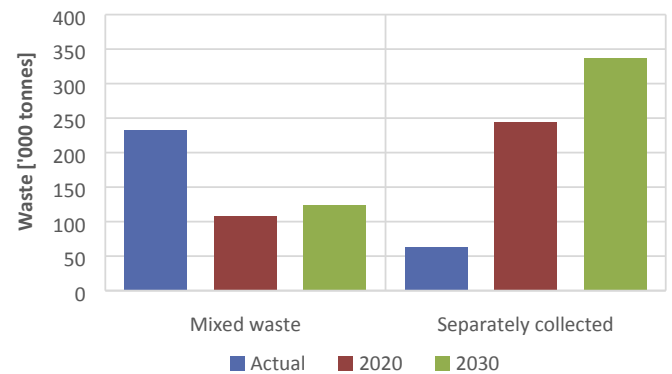
share of waste had to be replaced by biomass. The biomass price for the case of Denmark assumed was 28.58 €/t and was taken from Ref. [39].

3.2. Case of the City of Zagreb

Unlike Denmark, the Croatian WMS is not designed to meet the EU goals. Also, there is no actual WM plan for the City of Zagreb so technologies from WM plan to 2015 [40] were used for definitions of possible scenarios. The scenario Without MBT is based on the primary separation of waste and waste incinerator, while the scenario With MBT added MBT plant. For the WtE plant, as there is no existing incinerator, the same facility as in Sønderborg was assumed for the hypothetical cases. The major difference in WM status and the level of maturity of solutions in this field gives the Croatian case study a fundamentally different outcome. In comparison to the Danish case, WM procedures, legislation, and implementation are far from being optimally solved, and Croatia is faced with difficulties to resolve these issues and fulfil the commitment regarding the WM goals [41]. In the City of Zagreb, 300,000 tonnes of MSW is collected per year out of which 21% is separately collected, while the rest is collected as MW. Since there is no actual WM plan, waste quantities in future years were estimated using LCA-IWM prognostic model [28]. Actual and estimated data of separately collected waste fractions are shown in Fig. 4.

Today, separately collected waste is mainly used for material recovery (production of compost and materials), while MW is disposed on landfill Prudinec. Because of this unsustainable practice, two scenarios which, when implemented, can reach EU goals were analysed. These scenarios were developed according to the previously described methodology.

Fig. 4 shows possible waste collection data, if the primary separation of waste would be introduced and encouraged. The quantity

**Fig. 4.** Waste collection quantities.

of MW in the forecasted years has dropped by 50% in such scenario. This represents a challenge for planned WtE plant, but also a good opportunity to demonstrate the novel methodology of fuel switch between waste and biomass in the regions where a lot of work is yet to be done in WM.

There is no municipal waste WtE plant in Croatia, so there is no expected range of gate-fee value. Therefore this analysis will also help to determine the possible range of gate-fees in the case of the City of Zagreb. Waste incineration in Croatia is not taxed as in many other EU countries. WtE based CHP would be classified as high-efficiency CHP plant and the corresponding fixed feed-in tariff was used [42]. In new legislation WtE plants are recognized as a specific category and market-based tariff, with a proposed feed-in premium, but executive bylaws and regulations are not yet adopted. Furthermore, the heat price is constant as DH price in majority Croatia is considered to be a social aspect and regulated by politics through the government-owned operator. A discount rate of 5.5% is used which corresponds to discount rate in Public Private Partnerships in energy sector [43]. The analysis was performed on the same time-span as the electricity purchase agreement is signed for – 14 years.

4. Results and discussion

Based on previously described methods and case specific input data, results for the City of Zagreb and Sønderborg municipality are calculated.

4.1. Fuel data - case of Sønderborg municipality

In the case of the Danish municipality, expected waste increment trends are adopted – no major interventions in WMS are required and the most significant effect on waste generation are

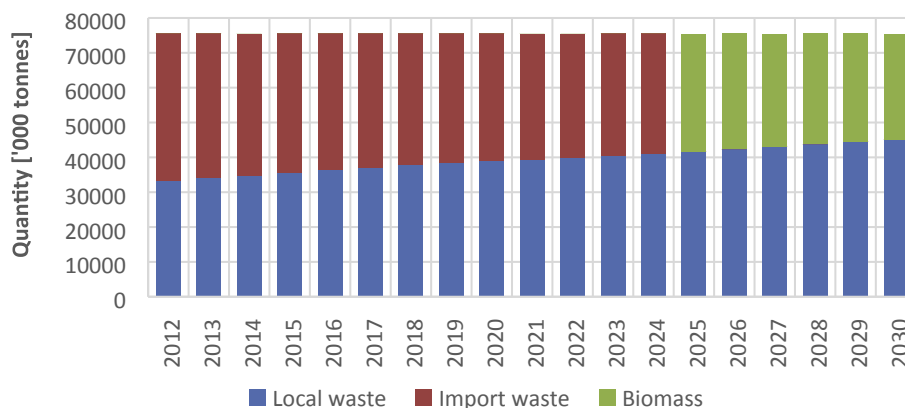


Fig. 5. Søndersborg plants fuel ratio.

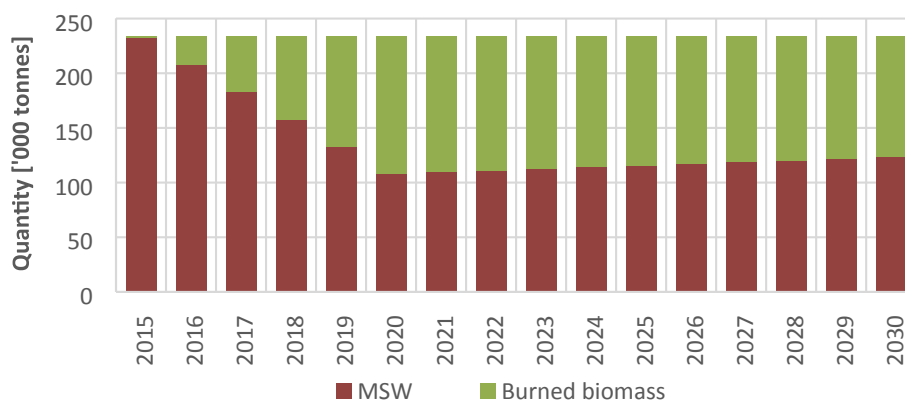


Fig. 6. MW quantities - Zagreb.

socio-economic movements. The impact of this trend on Søndersborg municipality incineration plant is shown in Fig. 5.

Because of the anticipated economic growth, more waste is expected to be locally generated, reducing the need for waste import. It is expected that the import of waste will be profitable until 2020 and probably even until 2025, although with reduced profits [20]. Hence, for both scenarios carried out for the case of Søndersborg WtE plant, a replacement of imported part of waste with biomass was assumed from the year 2025 until 2030 to compensate for the waste decrease. It is important to note here that the biomass used as a fuel for energy purposes is not taxed in Denmark, as it is considered as a renewable energy source, while waste is taxed in order to promote recycling over the waste incineration and landfilling [35].

4.2. Fuel data - case of the City of Zagreb

The Søndersborg municipality data can be compared with projections for Croatian capital, Zagreb, where WMS needs major interventions. To satisfy EU legislation, projections with rapid implementation of separate collections are performed (Fig. 6).

Until the 2020 quantity of MW is continuously reduced due to an increase of the share of separately collected waste. Rapid implementation of primary separation of waste to fulfil legislation goals for the year of 2020 reduces the quantity of waste that is collected in MW bins and overrides the increase in overall production of MSW due to trends described by WKC hypothesis. After 2020, a slower pace in the development of separate collection system is needed to satisfy legislation goals for 2030, so WKC

hypothesis trends in waste generation override decrease in the quantity of MW due to an increasing in penetration and intensity of primary separation of waste. In the period up to 2030, reaching the economic threshold is not expected, so increscent of waste quantity due to WKC hypothesis trends is expected. In these circumstances, the WtE plant has to be planned to satisfy waste disposal needs but also needs to preserve the economic viability of the investment. In this case, the planned size of incineration plant was 233,000 tonnes. As waste quantity decreases, new fuel needs to be introduced – the biomass. Changes in WMS introduced lead to changes in waste composition. As the primary separation of waste decreases quantities of components with low LHV, overall LHV of waste increases. In the second part, after 2020 goals are satisfied, the forecast shows that drop in the relative share of plastics which is the main cause of decrease of LHV in later years (see Fig. 7).

Further development of WMS can further decrease available

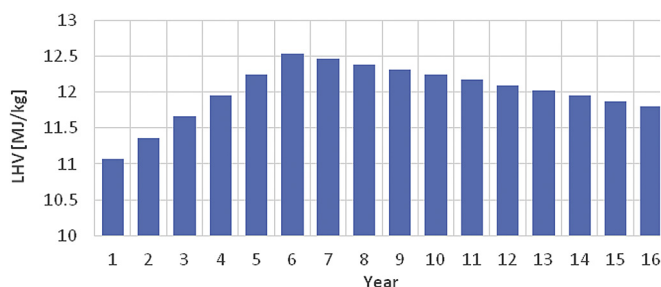


Fig. 7. LHV forecast - without MBT.

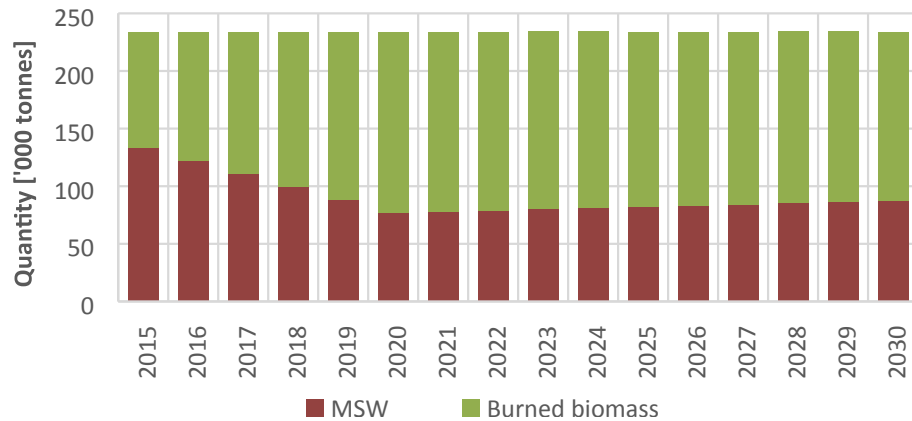


Fig. 8. Fuel compensation - with MBT.

waste for incineration. By the introduction of MBT, and by sorting of MW, more waste is extracted for material recovery which leads to increased demand for alternative fuels (Fig. 8).

The influence of implementation of MBT in the first year of the analysis on the same WtE plant operation was shown. While separation of waste components decreases waste quantity, it also has an influence on its heating value (Fig. 9).

The initial increase in LHV of waste, in comparison with the case without MBT, is due to separation of metals and glass stream, which have no calorific value, and bio-waste stream, which has low calorific value, in MBT facility. The continual decrease of LHV of MW is mainly the result of the increase in primary separation of waste which reduces quantities of paper and plastics, which are not separated in MBT facility and go to RDF stream, in collected MW. Therefore, separated collection of other wastes from waste stream continually reduces LHV of MW on the entrance of the incinerator.

Shown LHVs are calculated only for the MW, while a mixture of waste with biomass would have higher values in the first case, and lower in the second case. This is logical because of constant LHV of biomass in continental Croatia, which amounts to 12.24 MJ/kg for wood biomass with 30% of moisture, which depends on a variety of wood species that are used.

While in the case of Sønderborg WMS is established and gate-fee prices are defined, in the case of Zagreb they are to be defined. For the initial value of gate-fees, mean European value of 110 € per tonne of waste was used for calculation of minimal needed values. The method for determining gate price of biomass at the location was elaborated in Ref. [44]. The biomass originates from the capacities of Forestry Offices in the neighbouring counties. The changes in the mean price of biomass on the plant's gate, which is in the range between 32.2 and 37.13 €/t in both cases, show that there is enough biomass for the case examined (Fig. 10). These prices were calculated on the basis of the constant price of biomass

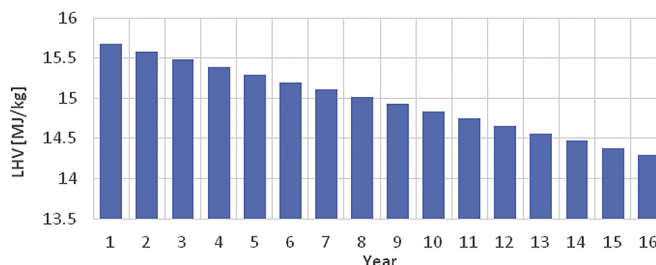


Fig. 9. LHV forecast - with MBT.

on the forest road of 32 € per tonne and fluctuating transport costs that depend on the distance of the plant from forestry offices from which biomass have to be transported.

The price of biomass increases as needed quantity increases, and vice versa, price decreases as the need for biomass decreases, because the price is considered to be a function of distance only so that it changes with every new forestry office that is included in calculation when the range of biomass collection increases.

4.3. Economic analysis - Zagreb

All scenarios for the case of the City of Zagreb were calculated on the basis of the same incineration plant whose data for full load are shown in Table 3.

Plant capacity was modelled on the basis of need for waste disposal without changing the existing WMS in 2015.

4.3.1. Scenario 1 – without mechanical biological treatment

Taking into account the influence of gate-fee on the price of waste collection, a yearly gate-fee was modelled as minimum gate-fee that ensures yearly cash flow of zero (after all expenses and investment cost). This also enables comparison of obtained data with Sønderborg case where WtE plant should not operate with a profit. On the same diagram data for the case without and with biomass, compensation can be observed. Also, minimal required constant gate-fee is shown in Fig. 11 for the 14 years period. The average gate-fee, which denotes mean price through all 14 years period, in scenario Without MBT is 75.76 €/t, while volatile, which denotes yearly changing gate-fee value, span between 6.21 and 107.69 €/t. When biomass compensation was introduced, average gate-fee drops to 20.22 €/t, and volatile is in the range from 6.05 to 26.74 €/t in absolute terms.

It can be observed that volatile gate-fee increases rapidly in first years. This is due to decreasing MW amount to 2020. After the 2020 gate-fee volatility is reduced and it's almost constant in compensated case due to an increase in waste amount but a decrease in its heating value. In the not compensated case increase in waste, quantity has much greater influence than the decrease of its heating value so the yearly gate-fee decreases.

4.3.2. Scenario 2 – with mechanical biological treatment

When MBT plant is introduced in WMS, the quantity of waste is reduced from the first year which increases the gate-fee. Values of gate-fees of this scenario are given in Fig. 12. The average gate-fee in scenario With MBT is –159.11 €/t, while the volatile span between –48.33 and –206.94 €/t. When biomass compensation is

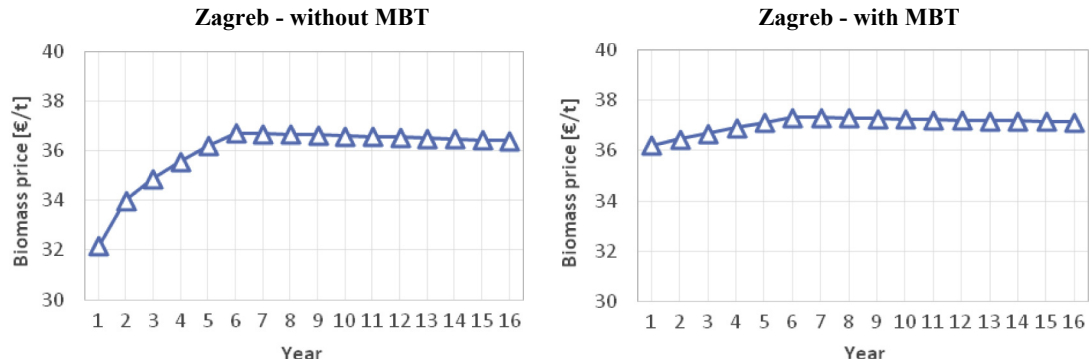


Fig. 10. Biomass price.

Table 3
Zagreb WtE plant data.

WtE plant Zagreb		
Capacity	14.3	MWe
	66	MWheat
Total O&M ^c	51.6	€/t
Investment cost ^c	10,700,000	€/MW
Efficiency el	16.6%	
Efficiency total	90.5%	
Availability	92%	
Analysis period	14	years
Initial gate-fee	−110	€/ton
Electricity feed-in income ^a	73.6	€/MWhe
Heat feed-in income ^b	34	€/MWht
Real discount rate ^d	5.5%	

^a Taken from Ref. [42].

^b Taken from Ref. [45].

^c Taken from Ref. [5].

^d Taken from Ref. [43].

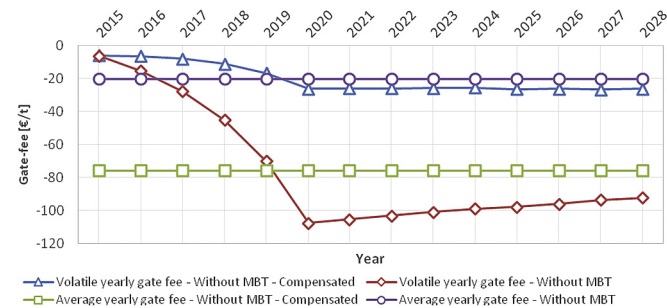


Fig. 11. Volatile yearly and average gate-fees needed to recover investment and running costs (negative sign denotes that the fee is paid to the generation plant rather than by the plant).

introduced, the average gate-fee drops down to −14.22 €/t, and volatile is in the range from −25.52 to 19.73 €/t.

From Fig. 12, it can be noted that even though the gate-fee is vastly increased in comparison with the scenario Without MBT when biomass compensation is introduced the gate-fee needed for economic viability is smaller than in the first scenario. This is due to a big increase in combined heating value of fuel and through greater energy production.

4.4. Economic analysis - Sønderborg

All scenarios for the case of the Sønderborg municipality were calculated on the basis of the existing Sønderborg WtE plant whose

data are shown in Table 2.

4.4.1. Scenario I – one energy market

Taking into account the expected future electricity market prices, as well as the rule that municipality owned WtE plants are not allowed to operate with profit, yearly gate-fees were obtained needed only to recover the investment and the running costs. On the same chart, an average fee until the year 2030 is presented. The average gate-fee could be used if the municipality would prefer a less volatile gate-fee price during the lifetime of the plant. These fees can be seen in Fig. 13. The average gate-fee for this case was 14.8 €/t, while the volatile gate-fee was in the span between 9.2 and 28.34 €/t in absolute terms.

Up to the year 2015, power prices on el-spot market were decreasing which meant that additional income from the heat market needed to be obtained, in order to recover the running and leveled investment costs of the WtE plant. From the year 2015 on, the average electricity prices are expected to increase, which will reduce the amount of income needed to be recovered from the heat market. The latter allowed the gate-fees to be reduced (in absolute terms).

It can be observed that the volatile gate-fee suddenly increases (in absolute terms) in the year 2025 as this is the year when importing waste will not be profitable anymore. Hence, in the year 2025, 41.1% of the fuel consisted of biomass and the rest from the waste collected within the municipality. As the biomass was more expensive than the waste, the gate-fee is needed to be raised in order to recover the biomass cost. The share of waste was then increasing up to the year 2030, in line with the forecasts of steadily increasing amounts of municipal waste, as discussed in the case study section. Using the gate-fees provided in Fig. 13 and economic data provided in Table 2, a WtE would have an NPV equal to zero, according to the municipality rules. Thus, it would not operate with a profit nor it would subsidize the heat consumption.

4.4.2. Scenario II – two energy markets

Nowadays, heat markets in Denmark are usually operated as monopolies owned by the municipalities. Although the latter can prevent excessive rises in prices due to the regulation, it can also discourage investments in energy efficiency as there is no real incentive for doing it. In order to assess the potential behaviour of the WtE plant on both power and heat markets, marginal prices based heat market was simulated in Matlab, while the power market simulation was carried out in EnergyPLAN. Both power and heat demand were modelled as fixed and known. Heat market was assumed to operate after the power market, i.e. by the time of the bidding on heat day-ahead market CHP producers already knew whether they were dispatched on the power market or not. It was

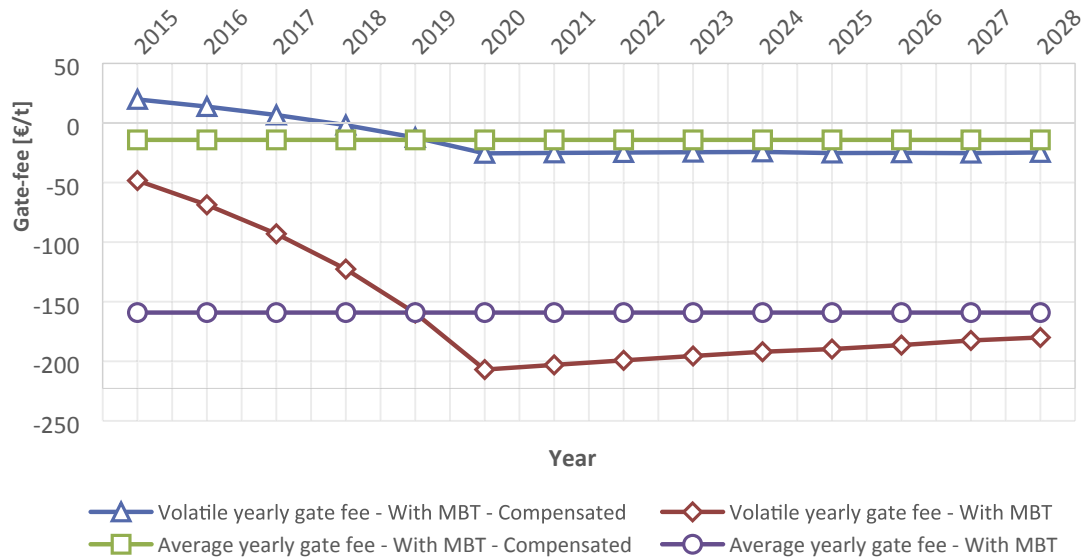


Fig. 12. Volatile yearly and average gate-fees needed to recover investment and running costs (negative sign denotes that the fee is paid to the generation plant rather than by the plant).

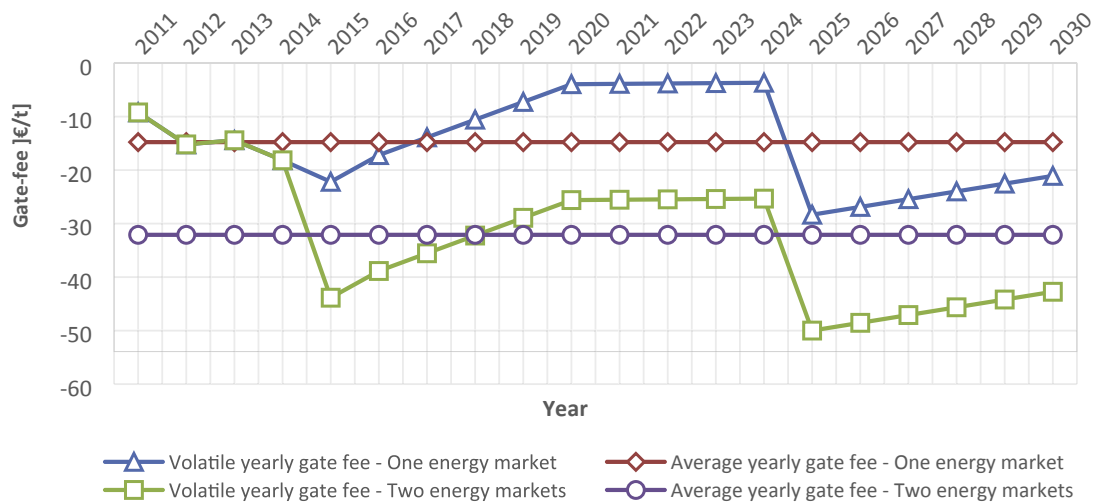


Fig. 13. Volatile yearly and average gate-fees needed to recover investment and running costs (negative sign denotes that the fee is paid to the generation plant rather than by the plant).

assumed that the plant started to operate on the day ahead heat market in the year 2015.

Marginal heat prices obtained from the Matlab, as well as DH hourly demand, can be seen in Fig. 14. It can be seen that during the time of high demand the heat prices were high, too. On the opposite, during spring and autumn, when there was a medium

demand for the heat, the marginal heat price was volatile. Finally, during the summer season when the demand for heat was low, the heat price dropped accordingly.

Due to the marginal heat day-ahead market, the WtE plant was not dispatched during all the hours of the year on the heat day ahead market. As a consequence, the needed gate-fee to recover investments and running costs during the lifetime of the plant needed to be higher in absolute terms than in One energy market scenario. Dispatching of the WtE plant on the heat market is shown in Fig. 15, while volatile and average gate-fees needed are shown in Fig. 13, together with the results of the with One energy market scenario.

By comparing Figs. 14 and 15, one can spot that during the time of the high demand the plant was constantly operating on the heat market. However, when the demand started to drop, the WtE plant was not operating in a constant way due to the larger generation of plants with lower marginal cost (solar thermal DH plant) or due to the conditions on the power market. It is important to emphasize

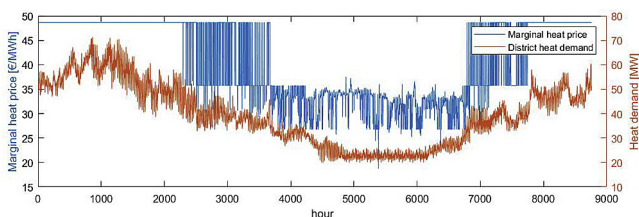


Fig. 14. Hourly marginal heat prices (left Y axis) and district heat demand in the city (right Y axis).

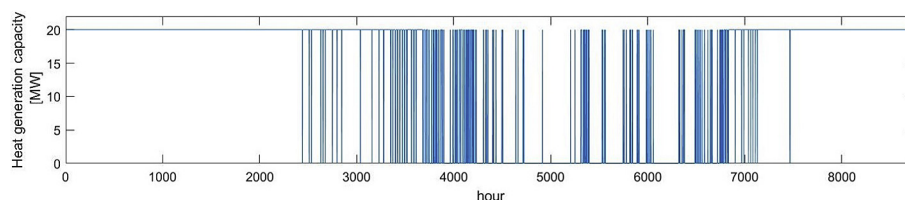


Fig. 15. WtE plant operation on the heat day ahead market.

Table 4

Comparison of the regulated and marginal price-based day-ahead heat markets for the year 2015.

	Regulated (averaged) prices	Marginal prices	Difference
Yearly turnover heat sales	14,770,440	14,889,000	0.80%
Waste CHP heat turnover	6,841,509	5,332,400	−22.06%

here that the second last term in Equation (2) shows that the WtE plant's marginal cost will be very dependent on the achieved power price on the el-spot market. If the obtained price is high, marginal heat price of the plant will be low and vice versa.

Finally, financial indicators of the regulated market and the marginal based day-ahead markets can be compared. As shown in Table 4, total yearly turnover on the markets is roughly the same in both cases. However, for the WtE plant, operating on both days ahead markets would be less beneficial, as it would receive 22.06% less income from the heat sales.

5. Conclusion

In this work, the analysis was carried out with the aim to analyse the influence of changes that are ahead of WtE plants. Therewithal, compensation for some of these changes is proposed. To test the approach, two WtE plants are taken as case studies, planned WtE plant in new EU member state which needs to fulfil EU legislation WM goals and in one old EU member state which is ahead of EU legislation in the area of WM. In the first case, the case of the City of Zagreb, the operation of planned WtE plant that satisfies needs of the city is analysed until 2030. In that period, because of needed WMS changes the majority of its capacity would be unused, less in the case of primary separation of waste alone and more in the case of introducing MBT plant. In these cases, fuel reduction is compensated with biomass which proved to be a sustainable way of alleviating this problem. This way the WtE plant is moved from the comfortable zone of regulated prices and put on the fuel market – the biomass market. The influence of this disturbance is tracked through gate-fee volatility analysis which enabled monitoring of economic viability of municipality-owned plants because of their social-economic influence on the population through the price of the waste collection. This introduction of the WtE plant on fuel market did make this plant economically viable again by reducing needed gate-fee under the value of land-filling gate-fee of 53 €/t [46], without incineration tax and with high electricity subsidy. In the second case, the case of the City of Sønderborg, where all EU waste legislation goals are met, the operation of existing WtE plant on day-ahead electricity market and at the same time day-ahead electricity and heat market is analysed and compared. Because heat market does not exist at this time, it is simulated on the principle of the day-ahead electricity market. It is shown that introducing heat market to WtE plants operation increases minimum needed gate-fee on the yearly level and exceeds maximum levels that are expected in Denmark of 40 €/t. Due to the operation of WtE plant on the heat market, the waste collection price would need to be increased. However, this depends on the price of

electricity, because dispatching time is dependent on marginal price which depends on electricity market price in every hour. Nevertheless, such open heat market could decrease heat price which could make it economically neutral on the basis of the municipality. Results of both of this analysis, carried out in completely opposite circumstances, show that WtE plant operation is economically viable during both of these transitions. Also, even though Denmark passed WM transition years ago and adapted to domestically waste reduction through waste import, its WtE plants will nevertheless need to undergo the same fuel switch which is designed for the transition of plants in the new EU member states.

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Paper 4 - The future of transportation in sustainable energy systems: Opportunities and barriers in a clean energy transition

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The future of transportation in sustainable energy systems: Opportunities and barriers in a clean energy transition



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ABSTRACT

Energy demand of a transport sector has constantly been increasing in the recent years, consuming one third of the total final energy demand in the European Union (EU) over the last decade. A transition of this sector towards sustainable one is facing many challenges in terms of suitable technology and energy resources. Especially challenging transition is envisaged for heavy-weight, long-range vehicles and airplanes. A detailed literature review was carried out in order to detect the current state of the research on clean transport sector, as well as to point out the gaps in the research. In order to calculate the resources needed for the transition towards completely renewable transport sector, four main alternatives to the current fossil fuel systems were assessed and their potential was quantified, i.e. biofuels, hydrogen, synthetic fuels (electrofuels) and electricity. Results showed that electric modes of transport have the largest benefits and should be the main aim of the transport transition. It was calculated that 72.3% of the transport energy demand on the EU level could be directly electrified by the technology existing today. For the remaining part of the transport sector a significant demand for energy resources exists, i.e. 3069 TWh of additional biomass was needed in the case of biofuels utilization scenario while 2775 TWh of electricity and 925 TWh of heat were needed in the case of renewable electrofuels produced using solid oxide electrolysis scenario.

1. Introduction

Transportation sector has proven to be one of the greatest challenges towards the sustainable development [1]. In the last decade, one third of the total final energy consumption and more than one fifth of greenhouse gas (GHG) emissions in the European Union (EU) have been a result of the fossil fuel-based transport sector [2]. Although the current trends in the heat and electricity sectors of some countries represent a significant progress in decreasing the demand and introducing more renewable energy sources (RES), the transportation still follows the old-fashioned trends of utilizing rising amount of fossil fuels. For example, Denmark has managed to reduce the heat and electricity demand over the past 30 years; however, energy demand in the transport sector has grown by almost 50% over the same period. Consequently, more energy is consumed in transport than in any other sector in Denmark [3].

Integrating electricity, heating and transport sectors enables higher penetration of renewable energy sources while battery electric vehicles (EVs), usage of more efficient forms of transport and introduction of alternative fuels can significantly decrease transport sector's depen-

dence on fossil fuels. However, there is no simple unique solution when it comes to implementing RES and reducing CO₂ emissions in the transport sector [1]. Therefore, numerous studies deal with the various possible solutions for the future sustainable transport sector. Whereas some researchers focus on the transport sector as a whole, many studies analyse only a certain mode of transport, technological solution or a planning scheme applicable in one or more sectors. The latter claim is supported by the literature review presented in the following paragraphs of this section. The literature review starts with the overview of renewable research on light vehicles (cars), i.e. EVs, hybrid electric vehicles, biofuels and hydrogen driven vehicles. It is followed by the overview of research on other transportation modes such as heavy vehicles, aircraft and marine transport. Finally, a few research papers that focused on transport as a part of the whole energy system are presented and the research gaps are explored.

Common research topics within the transport area include EVs and the sustainable road transportation. Overview of the current models of electric cars and their features were analysed in [4], including the current technological status, business models, policies and the future development with the focus on the Danish and the Swedish context.

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Nomenclature

AC	Alternating current	IEA	International Energy Agency
BAU	Business as usual	IoT	Internet of Things
BD_{demand}	biodiesel demand (TWh)	KER_{demand}	kerosene demand (TWh)
BET_{demand}	bioethanol demand (TWh)	LCA	Life cycle assessment
$Biomass_{demand}$	final biomass demand needed to produce biofuels (TWh)	LHV	Lower heating value
$BKER_{demand}$	biokerosene demand (TWh)	LHV_{BD}	lower heating value of biodiesel (GJ/ton)
BEV	Battery electric vehicle	LHV_{BET}	lower heating value of bioethanol (GJ/ton)
BTL	Biomass to liquid	LHV_{BKER}	lower heating value of biokerosene (GJ/ton)
CAPEX	Capital expenses	LHV_D	lower heating value of diesel (GJ/ton)
CEEP	Critical excess electricity production	LHV_{DME}	lower heating value of DME (GJ/ton)
CI	Compression ignition	LHV_{GAS}	lower heating value of gasoline (GJ/ton)
CNG	Compressed natural gas	LHV_{KER}	lower heating value of kerosene (GJ/ton)
CO_2_{demand}	CO_2 demand input for SOEC process, ton	LHV_{MET}	lower heating value of methanol (GJ/ton)
D_{demand}	diesel demand (TWh)	MET_{demand}	methanol demand
DC	Direct current	NREL	National Renewable Energy Laboratory
DME	Dimethyl ether	OECD	Organisation for Economic Co-operation and Development
DME_{demand}	DME demand (TWh)	OPEX	Operating expenses
EU	European Union	PHEV	Plug-in hybrid electric vehicle
El_{demand}	electricity demand input for SOEC process (TWh)	PM	Particulate matter
EV	Electric vehicle	PV	Photovoltaic
FCEB	Fuel cell electric bus	RES	Renewable energy source
FCV	Fuel cell vehicles	SEE	South East Europe
FT	Fischer-Tropsch	SEV	Small sized electric vehicle
GAS_{demand}	gasoline demand (TWh)	SOEC	Solid oxide electrolyser cells
GHG	Greenhouse gas	$Syngas_{demand}$	syngas demand for SOEC process (TWh)
HC	Hydrocarbons	USA	United States of America
$Heat_{demand}$	heat demand input for SOEC process (TWh)	V2G	Vehicle to grid
HEV	Hybrid electric vehicle	VOC	Volatile organic compound
HRES	Hybrid renewable energy system	η_{BTL}	total efficiency of BTL process (dimensionless)
IATA	International Air Transport Association	η_{fer}	total efficiency of fermentation process (dimensionless)
IC	Internal Combustion	η_{FT}	total efficiency of Fischer-Tropsch process (dimensionless)
ICT	Information and communication technology	η_{syn}	total efficiency of synthesis process (dimensionless)
		η_{system}	total efficiency of electrolyser (dimensionless)

Among many findings presented, key technological advantages of electric cars, such as reduced CO_2 emissions, noise and air pollution were emphasized. On the other side, a battery was detected as the key challenge regarding its cost, range, safety and life expectancy. An overview of electric vehicles' technical characteristics, fuel economy, CO_2 emissions and charging mechanisms was carried out in [5], where the author covered three different types of EVs – hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and full electric vehicles (FEVs). The authors concluded that electric vehicles have better fuel economies compared to other types of vehicles; however, if electricity generated for recharging the batteries is produced from oil or coal-fired plants, CO_2 emissions can sometimes be higher compared to the conventional gasoline vehicles. In a similar manner, a comprehensive review of EVs and related technologies provided in [6], pointed out the need for further advancement of research in this area to lower the price and improve the technical performances of an EV battery. A review of charging optimisation techniques for PHEVs and EVs, conducted by Rahman et al. [7], concluded that the development of charging infrastructure is a crucial element for the future growth of electric transportation. Technological and policy aspects of implementing EVs in the Lithuanian context were analysed in [8]. Using a SWOT analysis (Strengths, Weaknesses, Opportunities, Threats), the authors found that the breakthrough impact on the local EVs market can be created by attracting companies investing in battery production plants or plants for power trains production. However, in order to achieve the latter, a need for an active engagement of the government was emphasized. Furthermore, the cost of a rapid transition to EVs was assessed in [9], using Australia

as a case study. The latter study concluded that the transition to EVs can be achieved at approximately the same cost compared to the continued use of the conventional vehicles, if the battery costs fall rapidly and at about 25% larger cost if the battery costs remain high. In the heavy road transport sector, the development process and specifications of already existing heavy electric trucks were presented in [10]. The electric trucks are found to be useful for moving trailers in distribution centres, transport depots, container terminals and others. Developed electric trucks are quieter and require less maintenance than a diesel engine. Furthermore, Shafie-Khah et al. discussed the EVs in the electricity market context focusing on management schemes and vehicle-to-grid (V2G) technology, analysing the interplay between the transport sector and intermittent RES [11]. They argued that the spinning reserves and ancillary services markets will be the main targets of the EVs. They emphasized that in order to deal with uncertainties, such as the number of vehicles, price and time of charging, state of charge and driving patterns, stochastic techniques shall be used.

Expanding on these matters, integration of power and transport sectors was also a focus of many researchers. Christensen et al. [12] explored innovative business models to implement battery electric cars in Denmark, with the main emphasis on the interplay between electric vehicles and renewable energy generation. Their study concluded that some places, particularly Denmark, offer a great market and political setting to establish such business models in a successful way. A comprehensive review of research on the interaction between EVs and intermittent RES, carried out in [13], concluded that this kind of interaction is a very beneficial way to foster the development and

implementation of both technologies. The study in [14] emphasized that incentive-based policies for V2G technology are essential for the successful implementation of the technology. An explorative study on synergies between EVs and photovoltaics (PVs) indicates that in the current distribution network of a medium size European city, EV penetration level is limited to only 18%, whereas in the smart grid framework, with a high level of PVs, that share can be increased by up to 64% [15]. Other authors showed that 50% penetration of EVs in the four biggest cities in Croatia, in a combination with PV penetration of 50% of electricity demand, could reduce the import of electricity for more than 4 TWh [16]. Hu et al. [17] stressed that the management of EV fleet is necessary to create better optimized charging profiles and that proper engagement of commercial actors and EV owners is crucial for establishing a sustainable road transportation system. The importance of fleet management charging has been discussed in [18–20] where dynamic programming optimisation results were compared with the results obtained by an existing heuristic charging algorithm used in EnergyPLAN software. The Authors have illustrated the advantages of the dynamic programming algorithm in minimizing the charging energy cost (35% to 50% reduction compared to the base case) and satisfying the aggregate battery charge sustaining conditions.

Focusing on other potential pathways for the future transport sector, such as biofuels and hydrogen, the authors in [21] assessed the environmental impact of various biofuels, including bioethanol, biodiesel and bio-hydrogen. They concluded that even with the amount of fossil fuels required for biomass farming and biofuel processing today, biofuels can still contribute in reducing the fossil fuel usage. A review of Fischer-Tropsch (FT) synthesis technology for biofuel production, made by Ali and Dasappa [22], showed that the FT synthesis from biomass is a promising technique for production of renewable fuels. The highest bio-oil productivity was derived from palm oil. On the other hand, they emphasized that the latter process is only sustainable if the waste land is used for cultivation. Cultivating waste land for biomass production was assessed in [23]. However, the authors showed that the cultivated biomass for the case of Croatia is not economically feasible. Anderson [24] investigated the effects of biofuels use on vehicle emissions. He found that GHG emissions may decrease even with increased utilization of fuels while air quality is expected to decrease with the increase in the use of biofuels. Furthermore, biofuels are detected as a possible pattern to mitigate the increasing energy demand in the Australian transport sector [25] while for the case of Thailand [26], biofuels showed better environmental performance than their fossil-based equivalents. On the other hand, the water demand for their production is significantly higher. Reviewing alternative fuels for compression ignition (CI) engines, Datta [27] found that although biodiesel application results in significantly better environmental aspects than conventional diesel, it deteriorates the performance of the engine. Potential of introducing hydrogen as an alternative fuel was investigated in the Malaysian [28] and Australian [29] context. In both studies hydrogen was assessed as technically feasible and for the Australian case, it was shown that hydrogen fuel cell and battery EVs can fully replace fossil fuel vehicles by 2050. Due to its low gravimetric density, the main problems of hydrogen are its storage and transportation [30]. In order to tackle the latter issue, many storage options of hydrogen have been investigated, such as compressed gas, cryogenic tanks, metal hydrides or carbon nanotubes [31]. The storage problem was also emphasized in [32], where a comprehensive review of recent developments in hydrogen production, application and storage was provided.

Connolly et al. [3] developed production pathways in the context of a renewable energy system for various fuels, with the aim to establish an overall comparison between those fuels. They emphasized that electric batteries are not suitable for all modes of transport and thus other, energy dense fuels are needed. Moreover, biofuels are likely to be unsustainable in the context of 100% renewable energy system so other forms of fuels need to be investigated as well. Following that approach,

the authors in [33] analysed pathways for producing synthetic fuels with a special focus on solid oxide electrolyser cells (SOEC), combined with the recycling of CO₂. Synthetic fuel production was found to be beneficial for implementing high share of intermittent RES into an energy system, as it connects different sectors and makes the system more flexible. A conceptual design of an electricity-to-liquid fuel system made of SOEC stack working in co-electrolysis and a FT reactor was presented in [34], while the costs of synthetic fuel production using SOEC were assessed in [35,36]. It was found that pathways with higher share of biomass in the production process have the lowest costs; however they are not as flexible for wind integration as CO₂ recycling pathway. According to the authors in [37], a Power-To-Gas application by means of Renewable Hydrogen (H₂) production could be the viable solution due to its dual application: as a fuel for combustion or chemical conversion, as well as an energy storage medium for RES mismatch compensation. They found that when RES share ranges from 25% to 50%, using H₂ for heating purposes avoids the low round trip efficiency of its deferred electricity purpose. Eco-fuels production (different blends of hydrogen and natural gas) was found to represent a sustainable energy pathway on the local scale [38].

Many authors focused on technological solutions and planning schemes for other transport modes. A review of alternative fuels for the aviation sector, responsible for 2–3% of global anthropogenic CO₂ emissions [39], is provided in [40,41]. The authors in [42] examined the results from available measurements and proposed the first analytical approximation (ASAF) of the black carbon emissions reduction related with the usage of paraffinic alternative jet fuels. The conversion technologies for producing jet-fuels from biomass still need to undergo a considerable development to become economically feasible [35,36] while their competition with food production rises much awareness worldwide [44]. The study on prospects of biofuels in the Brazilian aviation sector [45] revealed that the high current demand of biodiesel for road vehicle fleet compromised the utilization of biofuels in other sectors, including the aviation. Furthermore, one possible economic route for the production of liquid fuels with high aromatics content, as an alternative to conventional bio-jet fuel production, was proposed in [46]. Another alternative for the aviation sector is solar powered aircraft system, a technology that is showing a potential to reach a major fraction of a future carbon-free energy portfolio in the aviation. However, it is necessary that the latter technology advances in order to overcome low conversion efficiency and high costs of currently available systems, with the energy storage being the key issue [47]. The most common used technologies for extracting and storing energy for solar-powered aircrafts today are silicon PVs and Li-ion batteries [48]. However, the authors argued that GaAs PVs and Li-S batteries are better suited for this use as the former technology is more efficient and the latter technology more energy dense [48].

Although limited in comparison to other sectors, different options have been analysed in the marine sector – namely fuel cell ships [49], supercapacitor ships [50] and different alternative liquid biofuels and synthetic fuels [43,44]. All the mentioned studies stressed the environmental benefits that the alternative solutions can bring, emphasized other strengths and barriers of those solutions and concluded that the serious research and development efforts are needed before they can become economically competitive. Furthermore, a well-to-tank analysis of various alternative fuels for Singapore's aviation and marine sector showed that the huge land use requirement for biofuels production will limit the availability of those fuels in Singapore [52]. Somewhat different solution for marine transport, a hybrid renewable energy system (HRES) for a ship, analysed in [53], proved to be a good alternative to reduce the GHG impact of the ship, implement new technological solutions in a conservative marine industry, achieve fuel savings and meet the new environmental policy regarding this sector.

Public transportation is also a common research topic within the field of sustainable transport. Hua et al. [54] concluded that technical

targets for commercialization of fuel cell electric buses (FCEB) in North America and Europe have already been met. Moreover, the cost comparison between three different types of buses, i.e. diesel buses, compressed natural gas (CNG) and V2G electric buses was conducted in [55]. State of the art sustainable public transportation projects indicate that this sector has a great potential in this context. For example, in Gothenburg, a new electric bus nine kilometre-long route, served by three all-electric buses and seven electric hybrids, started to

operate in June 2015 [56]. In China, around 16% of all city buses accounts for electric buses today, whereas 47,000 electric buses were sold only in 2014 and the first half of 2015 [57]. Moreover, Jaffery et al. [58] suggested a mass transit to solar powered railway transport system in Pakistan, in order to utilize country's huge potential for solar PVs and consequently reduce the fuel demand.

Some studies focused on modelling the future transportation sector taking a broad perspective; two scenarios utilizing electric vehicles and

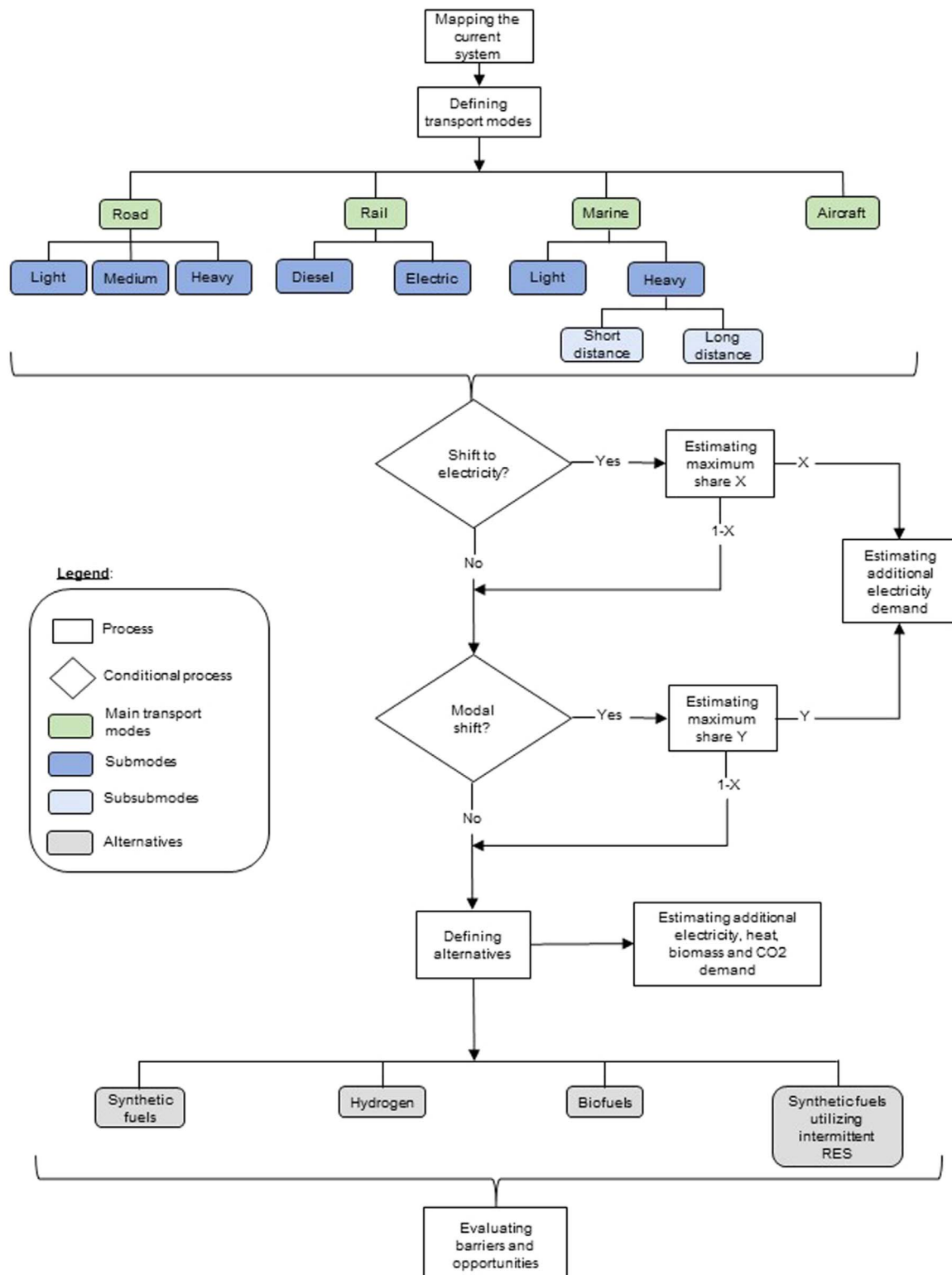


Fig. 1. Step-by-step process of estimating possibilities for transport sector transition.

hydrogen to high extent were presented for the case of Denmark [59], while four scenarios with different penetration of electric vehicles were analysed for the case of Sweden [60]. A fuel mix for the Indonesian road transportation sector for 2030, with 20% lower CO₂ emissions than the business as usual (BAU) scenario, was developed in [61] while energy efficiency potential in the transport sector for the case of Taiwan was assessed in [62]. Furthermore, the transport sector has been a part of models of 100% renewable energy systems in the EU [63] and the region of South East Europe (SEE) [64]. However, these studies have developed only superficial strategies about the transition of the transport sector, without detailed analysis of the limitations of each transportation mode.

As shown by the literature review, majority of the research papers and reports focused on battery electric vehicles, fuel cell vehicles and biofuels using conventional engines as the main alternatives to the currently existing transport sector, mainly driven by the fossil fuels. Moreover, they often focused on a specific transport sector, such as sectors of personal vehicles or marine transport. However, a lack of comprehensive research has been detected that would match the total additional energy demand for these cleaner alternatives with the scarce resources, as well as took into account the interaction between different transport modes. Additionally, still rising energy demand in the transport sector is contrasting the energy efficiency policies that are being promoted in the overall energy sector and thus, energy savings potential needs to be systematically assessed. Furthermore, as a variety of non-conventional alternatives are emerging, there is a rising need to review their current development status, calculate their potential and suggest new research areas that could be dealt with. Hence, this paper will expand the current state-of-the-art of by assessing the total resources needed for the main alternatives to fossil fuels in transport, on the scale of the EU, and by putting this demand into the perspective of the available scarce resources. A holistic approach has been taken into consideration in this paper, focusing on the interactions between different energy sectors and assessing different barriers and opportunities of the alternatives for penetrating the energy system on the more rapid scale. Utilizing a holistic approach, both energy savings potential and additional energy demand for cleaner fuels will be quantified on a system scale.

A proposed method for the shift of the transport sector towards sustainable one is presented in Section 2. Results, including the potential shift to electrified modes of transportation, alternative fuels production and the resource demand for it, are shown in Section 3. Sections dealing with the methods and results are followed by a discussion presented in Section 4 and an overview of the conclusions presented in Section 5.

2. Methods

Following the literature review presented in the introduction section, a method for the transition of the transportation sector towards 100% renewable one was developed. The clear focus of the method is to electrify the transportation sector as much as possible, i.e. the use of electricity as a primary energy input for the transport. Benefits of this transition are fourfold; first, a significant reduction in CO₂ emissions can be achieved if electricity is generated from cleaner energy sources compared to oil. Second, electrical engines are much more efficient compared to the internal combustion (IC) motors, which significantly increases energy savings in the system. Third, utilizing concepts such as V2G, in which the batteries of the vehicles can be used for storing the excess electricity generated and releasing the energy to the grid when there is a lack of supply, can integrate power and transport sectors, making the energy system robust and cheaper compared to the separately focusing on each of the energy sectors. Fourth, electric vehicles emit no emissions or harmful particulate matter from vehicles and thus, they do not contribute to the air pollution, an especially important issue in big, densely populated cities.

For the remaining part of the transportation sector, the part that cannot be directly electrified by the technologies existing today, several alternatives exist. Four of them are incorporated into the model developed in this paper. The developed model in a form of a logic tree is represented in Fig. 1 in detail.

Fig. 1 shows the process of modelling the transition of different modes of transport sector. The first step is the division of the transport sector into the main modes and further to lower level sub-modes where possible. In the latter step, the four main modes are identified, i.e. road, rail, marine and aircraft. The second step presents the evaluation of feasibility of the shift of fuel demand in each mode to electricity, followed by the estimation of the maximum possible share of the demand. A similar approach is used in the next step, in which the potential of a modal shift for the residual demand was assessed (residual demand is defined here as the demand after the maximum potential shift to electricity has been achieved). To clarify, the latter means that the part of the fuel demand in any transport mode that cannot be replaced by electricity, e.g. heavy road vehicles fuel consumption, can be shifted to another mode that has a higher electrification capability, e.g. electric railway. In the final step, alternatives are identified for the part that can neither be electrified directly, nor shifted to another electrified transport mode. In this stage, four alternatives were selected for the further quantitative evaluation, based on their technical and economic performances. For each of the alternatives, the main barriers, both technical and economic, as well as the main opportunities were analysed and presented in the following section.

After the estimation of the potential for the transition to electrical modes of transport had been performed and the alternatives for the residual demand determined, it was necessary to further elaborate additional alternatives for the remaining part of the transport sector. Therefore, three scenarios have been developed for meeting the residual demand by means of biomass, synthetic fuels and a combination of both. Before creating the scenarios, it was assumed that 57% of the residual fuel demand for passenger car vehicles was diesel (and the rest was gasoline), all the demand for medium vehicles, heavy vehicles and the marine sector was diesel and all the demand in the aircraft sector was kerosene. Assumptions according to the current trends in each sector are stated in [65].

In the *first scenario*, it has been assumed that all the diesel demand is replaced by biodiesel, gasoline by bioethanol and kerosene in the aircraft mode by biokerosene. Due to the differences in the chemical characteristics of fuels, a modified fuel demand was estimated using the lower heating value (LHV) of fuels, presented in Table 1. The calculation process is shown in (1), (2) and (3). In order to calculate the final biomass demand, process efficiencies showed in Table 2 were used. Efficiencies given in Table 2 present the total energy efficiency of the whole process – for the case of biofuels, from a raw biomass to the final product in a form of a liquid fuel. Furthermore, it was assumed that the 2nd generation biodiesel and biokerosene were produced by means of biomass to liquid (BTL) process and bioethanol through the fermentation process, as showed in (4). The final result obtained was the biomass (straw with 15% moisture content) demand needed to produce the estimated amount of biofuels.

Table 1
Lower heating value of different fuels [66].

Fuel	LHV [GJ/ton]
Methanol	19.9
Kerosene	44
Bio-diesel	37.8
Bio-ethanol	29.7
Gasoline	44.4
Diesel	43.4
Biokerosene	44
DME	31.7

Table 2

Total efficiencies of different processes used in the scenarios.

Process	Efficiency	Ref.
2nd gen. bioethanol fermentation	41%	[67]
2nd gen. biodiesel BTL	39%	[67]
2nd gen. biokerosene BTL	39%	[67]
Syngas synthesis methanol	67.3%	[66]
FT biodiesel & kerosene	51%	[66]
SOEC co-electrolysis	65%	[66]
SOEC assumed energy input distribution		
Heat	25%	[66]
Electricity	75%	[66]
CO ₂ demand for SOEC	[t/GJ output]	
CO ₂	0.105	[66]

$$BD_{demand} = D_{demand} * LHV_D / LHV_{BD} \quad (1)$$

BD_{demand} – biodiesel demand, TWh

D_{demand} – diesel demand, TWh

LHV_D – lower heating value of diesel, GJ/ton

LHV_{BD} – lower heating value of biodiesel, GJ/ton

$$BET_{demand} = GAS_{demand} * LHV_{GAS} / LHV_{BET} \quad (2)$$

BET_{demand} – bioethanol demand, TWh

GAS_{demand} – gasoline demand, TWh

LHV_{GAS} – lower heating value of gasoline, GJ/ton

LHV_{BET} – lower heating value of bioethanol, GJ/ton

$$BKER_{demand} = KER_{demand} * LHV_{KER} / LHV_{BKER} \quad (3)$$

$BKER_{demand}$ – biokerosene demand, TWh

KER_{demand} – kerosene demand, TWh

LHV_{KER} – lower heating value of kerosene, GJ/ton

LHV_{BKER} – lower heating value of biokerosene, GJ/ton

$$Biomass_{demand} = \frac{BD_{demand}}{\eta_{BTL}} + \frac{BET_{demand}}{\eta_{fer}} + \frac{BKER_{demand}}{\eta_{BTL}} \quad (4)$$

$Biomass_{demand}$ – final biomass demand needed to produce biofuels, TWh

η_{BTL} – total efficiency of BTL process, dimensionless

η_{fer} – total efficiency of fermentation process, dimensionless

In the *second scenario*, diesel was replaced by DME, gasoline by methanol and kerosene by biokerosene, the latter being the same as in the first scenario. Both synthetic diesel and methanol were assumed to be produced through the SOEC process. Firstly, the modified demand was calculated using the same method explained for the case of *scenario 1*, shown in (5) and (6) for DME and methanol, respectively. Next, the syngas demand was estimated using the assumption that the synthetic diesel was produced from syngas through the Fischer-Tropsch process, whereas methanol was a product of the syngas synthesis, explained in (7). Finally, electricity, heat and CO₂ demand needed to produce the estimated amount of syngas was calculated, showed in (8), (9) and (10) respectively. The biomass demand to produce the biokerosene was calculated, too.

$$DME_{demand} = D_{demand} * LHV_D / LHV_{DME} \quad (5)$$

DME_{demand} – DME demand, TWh

LHV_{DME} – lower heating value of DME, GJ/ton

$$MET_{demand} = GAS_{demand} * LHV_{GAS} / LHV_{MET} \quad (6)$$

MET_{demand} – methanol demand

LHV_{MET} – lower heating value of methanol, GJ/ton

$$Syngas_{demand} = \frac{DME_{demand}}{\eta_{FT}} + \frac{MET_{demand}}{\eta_{syn}} \quad (7)$$

$Syngas_{demand}$ – syngas demand for SOEC process, TWh

η_{FT} – total efficiency of Fischer-Tropsch process, dimensionless

η_{syn} – total efficiency of synthesis process, dimensionless

$$El_{demand} = Syngas_{demand} / \eta_{system} * 75\% \quad (8)$$

$$Heat_{demand} = Syngas_{demand} / \eta_{system} * 25\% \quad (9)$$

$$CO_{2,demand} = Syngas_{demand} / \eta_{system} * 0.105 \quad (10)$$

El_{demand} – electricity demand input for SOEC process, TWh

$Heat_{demand}$ – heat demand input for SOEC process, TWh

$CO_{2,demand}$ – CO₂ demand input for SOEC process, ton

η_{system} – total efficiency of electrolyser, dimensionless

Lastly, in the *third scenario*, kerosene was also assumed to be produced by means of electrolysis. Synthetic kerosene production followed the same pathway as the synthetic diesel production explained earlier. This resulted in higher additional heat, electricity and CO₂ demand than in the *second scenario*. However, there was no additional biomass demand. This scenario was calculated according to the same method as explained in the *second scenario*, while only the synthetic kerosene demand was added in (7) which resulted in a higher syngas demand.

Nevertheless, evaluation of synthetic fuels production utilizing intermittent RES was carried out as a part of one of the alternatives. To do so, the EnergyPLAN model has been used [68]. The EnergyPLAN is a deterministic input/output model with the main purpose of analysing future energy systems. It is a simulation model, operating on an hourly time resolution. It has been already used to model numerous 100% renewable energy systems on various scales, from municipality [69] to the European level [70]. A detailed description of advantages and disadvantages of the model, as well as a brief comparison with other modelling tools, was given in [64].

3. Results

3.1. Mapping the current transportation modes and assessing the potential for clean transition

Following the method described in Fig. 1, the estimation of different transport means and their energy consumption was carried out. This was done using the Odyssee report [71] with the year 2013 taken as a base year. The share of different transportation modes can be seen in Fig. 2.

The final energy consumption of transportation sector in 2013 was 348.8 mtoe or 4056.5 TWh [72]. Further results of more detailed mapping of transportation modes can be seen in Table 3.

The more detailed division of the transport means is needed in order to be able to calculate the modal shift potential realistically, as well as to estimate the maximum possible transition to the electrified vehicles of the same type in a reasonable way (for example, IC cars to battery electric cars). Due to the serious constraints in finding the detailed enough literature dealing with the different types of ships and their respective shares in total energy consumption, marine mode of transportation was left out of the potential modal shift analysis. As it is consuming only 1% of the total final energy consumption in the transport sector, this simplification did not have a significant impact on the overall result. However, it is worth mentioning that a certain share of it could be electrified already today as stated in Table 4.

Table 4 presents possibilities of shifting transportation modes to

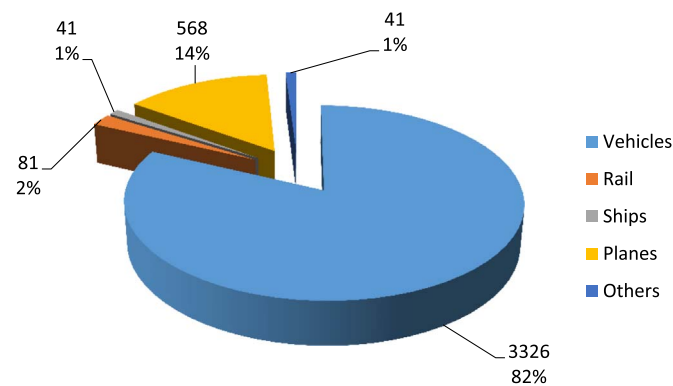


Fig. 2. A share and absolute values of the end use energy consumption for different transportation modes in the EU [TWh] [71].

Table 3

Mapping of share of different transportation means.

Transport mode	Transport sub-mode	Share of sub-mode in the transport mode	Ref.
Road	Light	59%	[71]
	Medium	23%	[71]
	Heavy	18%	[71]
Rail	Electric	80%	[73]
	Diesel	20%	[73]
Marine	No sub mode		
Aircraft	No sub mode		

electrified ones, as well as the modal shift potentials, that are possible already today, based on the references stated.

After taking into account all the measures presented in Table 4, it was calculated that the potential decrease in the demand for fossil fuels can reach a significant amount of 2931.3 TWh. Due to the shift to more

Table 4

Detected possibilities of shifting the transport modes to electrified ones.

Measure	Ref.	Discussion
Shift of 87% of passenger cars fuel demand to electricity	[73]	Technical potential based on the analysis of 3715 different vehicle profiles in the period of three weeks. It has been concluded that 87% of profiles can be fulfilled by battery electric vehicles (BEVs).
Shift of 70% of medium-heavy vehicles fuel demand to electricity	[4,74]	Electric vans have a proven range of up to 160 km, and from [4] it can be estimated that they can be used in 70% of the cases. Additionally, up to 10% of the vans can be replaced by small sized electric vehicles (SEV) [74].
Shift of 90% of heavy vehicles fuel demand to electricity (modal shift to electric rail transport)	[75,76]	TREMOVE model showed that 78% of the heavy duty truck transport emissions could be cut by modal shift to electrified trains [76]. In [75], an assessment of numerous different studies was carried out. Out of many other examples, TRANSCARE model estimated the potential of modal shifts of 5%, 40% and 100% on the distances of 50–150 km, 150–500 km and > 500 km, respectively. Furthermore, it is stated that for the case of Switzerland, the share of rail freight transport is equal to 66% already today. Based on studies presented, assuming the right policy measures and internalization of external pollution costs take place, up to 90% of heavy transportation vehicles could shift to electric rail transportation mode.
Shift of all the remaining diesel railway transportation to electricity	[59,77]	Adopted from the two scenarios in which the Danish railway sector is fully electrified in the year 2050 [59]. Furthermore, in [77] it was shown that the electrified trains share increased from 30% to 53% between 1990 and 2009 and from 53% to 80% until the year 2012. Hence, the total electrification of the railway system is possible already today.
Shift of 20% of light ships and 10% of heavy ships fuel demand to electricity	[51,78,79]	Diesel-electric ships could reduce the fuel demand by 30–50% [78]. Moreover, small ships powered by wind turbines and solar PVs, as well as fully electric battery ships are already in a commercial use [79]. However, less optimistic assumptions have been made to stay on the safe side, based on the fact that majority of the ships will still use liquid fuels in the future [51].
Modal shift 12.2% of aircraft sector demand to electric rail transport	[80–82]	In [39] and [40] it was shown that the short-distance flights can be challenged by high-speed trains. The reason is the long layover time at airports, as well as the travelling time to and from the airports which are usually located outside of the city. More specifically, in [80] for the case of Germany, it was shown that on distances of up to 500 km high speed railway is better option than airplanes. In [81], for different countries including Japan, France, England and others, it was shown that the majority of share on distances below 500 km are serviced by high-speed trains rather than planes. Based on [82], it was calculated that in terms of flown kilometres, the share of short distance flights (< 500 km) in Europe is 15.2%. Finally, it was assumed that 80% of these flights can be replaced by high-speed electrified trains.

efficient electrical modes of transport, the energy demand for the same amount of travel distance dropped from 2931.3 to 880.3 TWh, using efficiencies as defined in [68]. The remaining demand for fossil fuels of 1125 TWh cannot be directly electrified by the technologies available today and thus, alternatives need to be considered.

Alternatives that were assessed quantitatively by the authors are: synthetic fuels, hydrogen, biofuels and synthetic fuels utilizing excess electricity generation from intermittent renewable energy sources. Differences between synthetic fuels and synthetic fuels production utilizing excess electricity is that the latter assumes lower marginal prices of electricity that can be utilized, as well as increased possibility of integration of larger capacity of intermittent energy sources, creating additional demand for electricity that can be flexible. The choice of assessed alternatives is by no means statement that there are no other possibilities for the transition of the remaining part of the fossil fuel driven transportation sector; it is rather the choice for addressing the impact of highly discussed transition pathways in research community on a wider scale, including the real potential of renewable resources that are available for the transportation sector.

3.2. Results of scenarios

Using the scenarios developed and presented in the previous section, additional demand for alternative resources was estimated. Biomass scenario showed that for the production of biofuels for the remaining part of the transportation sector, which cannot be electrified today, there is a demand for 11,048 PJ or 3069 TWh of biomass.

In the scenario that considered production of synthetic fuels from the mix of biomass and heat and electricity utilized in electrolyzers, the demand for biomass was calculated to be 1279 TWh, additional electricity and heat demand were estimated to be 1646 TWh and 549 TWh, while the CO₂ demand was 539.21 Mt. Thus, reduced biomass demand was complemented by increased demand for electricity and heat.

Finally, the third scenario considered production of synthetic fuels solely from heat, electricity and CO₂. Although in this scenario there is no additional demand for biomass, there is a significant increase in demand for heat and electricity, calculated to be 925 TWh and 2775 TWh, respectively. Furthermore, demand for CO₂ in this scenario was calculated to be 908.98 Mt.

3.3. Detected barriers and opportunities for alternatives assessed

3.3.1. Synthetic fuels / Electrofuels

Following the terminology presented in [83], it is important to distinguish between the terms *synthetic fuels* and *electrofuels*. Whereas *synthetic fuels* refer to fuels produced from various fuels, including coal, gas or biomass through the FT process, the term *electrofuels* refers to the fuels based on the conversion of electricity to liquid fuel. Also, the production process of electrofuels does not include any fossil resource input; it is rather based on recycling CO₂ emissions and an electrolysis process powered by electricity. If both the carbon and the electricity are produced from RES, then the term *renewable electrofuels* can be used. On the other hand, the only renewable pathway of *synthetic fuels* production is biomass-to-liquid process. The fuels assessed in this paper are exclusively *electrofuels*, as their production process is based on SOEC co-electrolysis and syngas synthesis or FT synthesis. The following sections, however, include both *synthetic fuels* and *electrofuels*, as most studies usually do not make a clear distinction, or simply do not define the exact production process and thus, it is not possible to clearly define the exact term. On the positive side, the majority of the matter in this section – barriers and opportunities of synthetic and electrofuels – can be applied to both.

3.3.1.1. Economic barriers. Well to wheel energy efficiency from electricity for different synthetic fuels for the case of the Swedish transport sector was analysed in [84]. Authors analysed three different types of synthetic fuels to be used in IC engines, namely methane, methanol and FT-diesel, as well as hydrogen for fuel cell electric vehicles. Estimated well to wheel efficiency has been 25% for hydrogen and 14.3%, 13.5% and 12.6% for methane, methanol and FT-diesel, respectively. The same study estimated that for the case of the Swedish system, FT-diesel was competitive in the market only in the most optimistic scenario, whereas other investigated fuels had the potential to become competitive to fossil fuels and other renewable fuels especially. Hence, in order to increase the penetration of these types of fuels, either both the technology and running costs will need to go down, or the prices of fossil fuels would need to significantly rise in the future.

3.3.1.2. Technical (infrastructure & environmental) barriers. Authors in [85] emphasized the two main challenges the electrofuels are faced with when produced from renewable power. The first challenge is the fluctuation of the renewable energy sources, implicating low number of full load hours, which leads to the need of intermediate storage, fast response time of the electrolyser and high installed capacities. The second challenge is related to the possible high production costs due to the high electricity price, which may affect achieving the market price competitive level. Therefore, further electrolyser cost and efficiency improvements are necessary to reach the market entry level.

Analysing the atmospheric emissions from synthetic and electrofuels, they are heavily dependent on the resource input used for the production, as well as the production process itself. If produced through the biomass-to-liquid and FT synthesis (synthetic fuels), or CO₂-hydrogeneration using the renewable electricity and CO₂ from combusting biomass (electrofuels), then these fuels are considered

carbon neutral, as every part of the production cycle is carbon neutral [83]. However, even in that case, often forgotten consequence of these fuels is the emission of CO, NO_x, benzene and particulate matter (PM).

Expanding on the matter of emissions, Ridjan [86] elaborated the environmental properties of the three main electrofuels – methanol, dimethyl ether (DME) and methane. In one of the biggest methanol consumers in China, the Shanxi province, CO, NO_x and benzene emissions dropped by 20% and PM by 70% after introducing methanol in the transport system. Moreover, along with no CO₂, exhaust emissions from DME have no CO and NO_x, as well as no sulphur products. This makes DME the most beneficial alternative fuel from the emissions stand point. The study in [87] explored the NO_x emissions of alternative diesel fuels and found that FT diesel results in 21–22% lower NO_x emissions compared to the conventional diesel fuel. Somewhat different conclusion was made by authors in [88], who found that FT diesel caused higher NO_x emissions than the conventional ultra-low sulphur diesel, however PM emissions were found to be lower.

In order to increase the penetration of these types of fuels, either both the technology and running costs will need to go down, or the prices of fossil fuels would need to significantly rise in the future. On the other side, even if the technological and economic constraints will be successfully resolved, air pollution will still be an issue in the future. Somewhat contradicting research about emissions comparison of conventional and alternative diesel fuels show that more research needs to be carried out in this area.

3.3.1.3. Opportunities. As stated in [35], all synthetic fuel and electrofuels-related technologies are still in the R & D phase and therefore the costs of those technologies are very uncertain and can only be based on predictions and available stack costs. The study also concludes that they have higher production costs than the liquid fuels produced from biomass; however, synthetic fuel production pathways are more flexible in terms of wind power integration, which might be of high importance in the future energy systems.

Considering the engine design and the infrastructure, some synthetic fuels, like methane, require minor adaptations of the engine technology, while FT-diesel, for example, can be immediately used in the current systems [84]. This distinguishes them from, for example, biofuels that are currently available, as they require mixing with conventional fuels or a re-design of an engine. Furthermore, they can utilize already existing infrastructure built for fossil fuels, such as oil and gas pipelines, storages and charging stations. This makes them particularly interesting for urban areas, where larger infrastructure changes and actions might represent a challenge and cause inconvenience for the citizens.

This leads to the conclusion that the economy of synthetic and electrofuels highly depends on the future efforts in R & D, while regarding the infrastructure they are ready to be implemented into the existing system.

3.3.2. Hydrogen

3.3.2.1. Economic barriers. According to [89], today's global hydrogen market is currently valued at around \$420–500 billion annually, with a 20% annual growth rate. It is however centred on the petrochemical industry where \$107 billion p.a. is spent on production of hydrogen. Authors conclude that if the use of hydrogen is to be made widely available for merchant consumption, its production costs need to be reduced to become competitive. Another barrier is a high investment costs of the new infrastructure, as stated in [90,91] and explained into more details in the next paragraph.

Nowadays, the cheapest option for producing hydrogen is steam

reforming of hydrocarbons. Utilizing the latter technology coupled with CO₂ sequestration could be an alternative if the “sustainable” routes prove to be too expensive in the future [92]. However, production of hydrogen in this way would curb the potential of power-to-gas technologies in balancing the power grid, seriously limiting the penetration of renewable energy sources.

3.3.2.2. Infrastructure barriers. Introducing the hydrogen driven fuel cell vehicles (FCV) into the transportation sector represents various technical and non-technical challenges. One of the main infrastructure challenges is building a suitable supply chain for automotive fuel cell parts, due to the fact that existing suppliers are usually not acquainted with the fuel cell technology or equipped to produce large amount of units at close to zero defect rates and low costs [90]. Authors in [91] stated that implementing FCVs requires a completely new fuelling infrastructure, as well as that currently hydrogen is supplied by specialized companies and not by the existing transport fuel industry. The latter is however seen as an opportunity to create new businesses and a chance for new players to enter the market. According to [93], hydrogen energy infrastructure development is often considered as an insurmountable technical and economic obstacle to the use of hydrogen as an energy carrier.

3.3.2.3. Benefits and opportunities

3.3.2.3.1. Air quality. Hydrogen is a clean fuel that generates no particulate or NO_x emissions, which is very beneficial for the air quality, especially in congested cities. Downstream products of fuel cells are water and heat. The environmental impacts with other phases in the life cycle of a hydrogen system are similar to those for other energy technologies and may be small or large, mainly depending on the source of hydrogen [94]. If the electricity used in electrolyzers was produced from renewables it can be concluded that no CO₂ emissions were generated in the whole process. Furthermore, even if the gas is used for electricity generation, CO₂ emissions would be produced from point source, which could be easier to deal with utilizing different technologies, as opposed to CO₂ emissions emitted in exhaust gases of moving vehicles.

Gasoline vehicles cause much higher ambient concentrations of pollutants compared to the FC vehicles. For the case of Sacramento, California, gasoline scenario produced 273 times greater CO, 88 times greater VOC, 8 times greater PM₁₀ and 3.5 times greater NO_x concentrations compared to the hydrogen pathway [95]. The introduction of FC vehicles in the light duty vehicles in California was part of the research carried out in [96]. They have shown that significant reductions in ozone and PM_{2.5} can be achieved in the year 2050, when FC vehicles market share reaches 50–100% market share.

3.3.2.3.2. Distributed production. Because of the low volumetric energy density of hydrogen, its distribution energy use is rather expensive and energy-intensive. Investment and pumping-power requirements are greater than for natural gas. Large-scale hydrogen distribution by pipeline adds \$1–2/GJ to hydrogen production costs. Distribution of liquid hydrogen is more costly (\$7–10/GJ) as energy is needed for liquefaction at –253 °C. Refuelling stations may add \$3–9/GJ to H₂ costs [97]. Hence, one suitable approach would be to produce hydrogen in on-site electrolyzers, located in fuel stations or even in the home charging stations. In this way, already existing infrastructure in terms of power grid would be utilized as electricity would be distributed instead of hydrogen. This could prove to be a notable incentive for the local communities to engage in the transition, as distributed generation of hydrogen would provide many benefits to local communities directly, in terms of infrastructure benefits and jobs creation and indirectly, in terms of reduction of payments for importing fossil fuels. Active inclusion of citizens in the transition could give impetus to quicker

adoption of the emerging technology.

3.3.2.3.3. Long-distance heavy-weight vehicles. One of the opportunities for the hydrogen is its use in long distance heavy-weight vehicles, such as trucks, unsuitable for current stage of development of battery electric vehicles. Nikola Motor Company unveiled its highly anticipated Nikola One fuel cell truck in December 2016 [98]. It has a range of 800–1200 miles while delivering over 1000 horsepower with zero emissions. In Norway, a recently started project is aiming for production of four hydrogen powered trucks and 10 forklifts for the largest food distribution company in Norway [99]. However, it is still unclear whether these trucks will use fuel cells or hydrogen internal combustion engines. Fuel cell stacks using Proton Exchange Membrane technology, suitable for use in trucks have already been produced and delivered in unnamed European company for testing [100].

Both barriers and opportunities are significant in terms of hydrogen driven transport sector. In future research it will be important to holistically model hydrogen conversion as a part of energy system, as production of hydrogen can increase flexibility of the power system, as well as significantly improve the air quality of the future cities. Too narrow focus on hydrogen technology itself does not capture these pros and thus, can lead to worse socio-economic indicators than it is in reality. Furthermore, the potential of local job creation in distributed hydrogen production infrastructure should be seriously investigated in the future, comparing the benefits of local production with the anticipated economies-of-scale of a mass, centralised production.

3.3.3. Biofuels

3.3.3.1. Economic barriers. One of the conclusions from the study that compares biofuel production and food security [101] was that “increasing biofuel production will have impact on world agricultural commodity prices and food security at global, national, household and individual levels”. Furthermore, authors in [102] estimated that increased biofuels production caused 12% rise in global food prices, of which US biofuel production accounts for 60% of the total rise.

Another argument is that biofuels have a potential to lower fossil fuel prices, creating therefore a “rebound effect” of returning to the fossil fuels [103].

Furthermore, a significant economic barrier can be seen in terms of available renewable biomass. Next to the transportation sector, both power and heat sectors are increasingly utilizing biomass as a form of the clean and renewable technology, lowering the amount of sustainable biomass available.

3.3.3.2. Technical (infrastructure & environmental) barriers. Authors in [3] summarized the main barriers of biofuels as follows: limited amount of residual bioenergy sources from agriculture, waste or forests; high land demand if the purpose of crops is only production of biofuels; land alternative for biofuel production is often food production. Life Cycle Assessment (LCA) of biomass-based energy systems performed in [104] showed that the use of crops to fulfil the biofuel demand for heavy transport, ships, defence and aviation caused significant environmental impacts on global warming, eutrophication and land usage.

One of the largest barriers of the biofuels is that the existing IC engines need to be optimized or re-designed in order to be suitable for biofuels, or biofuels need to be blended with the conventional fuels, which in turn leads to higher GHG emissions. Moreover, if the fuel is adapted to suit the existing technology, it is important to consider that the more the fuel is processed the lower is the overall system efficiency

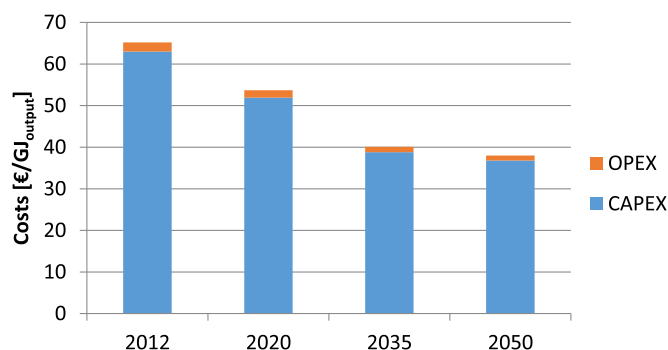


Fig. 3. CAPEX (Capital expenses) and OPEX (operating expenses) for DME production.

[105].

Furthermore, despite the fact that the cycle of producing and consuming biofuels is considered carbon neutral, if the biomass resources are utilized in a sustainable way, NO_x emissions of most biofuels are at a comparable level with the conventional diesel fuel [106]. Some studies found that biodiesel in some cases actually increases NO_x emissions, while it reduces hydrocarbons (HC), CO and PM emissions in comparison to the petroleum diesel fuel. The reasons for such an effect may lie in the influence of biofuels on injection time, ignition delay or combustion temperatures.

The study in [52] analysed the process chains to supply various fuels for the Singapore's aviation and marine sector, including biofuels produced from the crude palm oil, applying a well-to-tank analysis. It showed that looking at the overall life cycle of biofuels production from the palm oil, including cultivation of oil palms, extraction of oil, transport of oil and the final production of the fuel, results in the GHG emissions that can be even higher than emissions associated with the production of the conventional diesel fuel, depending on the palm cultivation rate. Moreover, a huge land use demand makes this type of fuel highly unlikely to replace a substantial level of traditional fuels in the future.

3.3.3.3. Opportunities. Advantages of using biofuels are however numerous, especially considering the current market and technology development state. Firstly, the cost of producing biofuels is considerably lower than the cost of producing hydrogen or synthetic and electrofuels, but currently still higher than the cost of producing fossil fuels. Next, they can be produced from a wide range of materials, from wood biomass and residuals to crops and edible oils. For example, on EU level several first, second and third generations of biofuel production technologies were considered [107]. It was found that the most promising raw materials for economical production of biofuels are miscanthus and algae, while biofuels could replace significantly more than 10% of the fossil fuels without significant impact on the EU's food supply chain. Finally, although biofuels have some negative impact on the air quality (increased NO_x emissions), they generally contribute in reducing GHG emissions, including CO_2 , CO and especially PM [108].

Considering biomass, future research and technological advances should focus on the 2nd generation of biomass, in order to avoid the competition with food production land use. Moreover, a holistic modelling of the biomass supply chain is needed in order to assess its demand along with the biomass demand in heating and power sectors, as focusing only on the transport sector could lead to the excess use of biomass, making it unsustainable. On the other hand, even if the biomass use will be sustainable from the CO_2 point of view, rapidly increasing urban population will need to cope with high air pollution emissions from biofuels and thus, further technological advances in internal combustion engines (ICE) and the exhaust systems of vehicles will be needed in order to improve the socio-economic costs of the

transport systems in the future. Due to its economically sound performance compared to the other alternative fuels, it should be considered as a potentially cost-competitive technology to fossil fuels, especially for the part of transport sector that is hard to electrify with the current state of technology, such as aviation and heavy duty vehicles.

3.3.4. Synthetic fuels utilizing intermittent renewable energy sources (PV)

Synthetic fuels can be produced by co-electrolysis from CO_2 and H_2O with the large amount of electricity. One of those fuels is DME and it is considered to be a viable substitute for diesel fuels, being able to use the same systems and infrastructure.

If the excess capacity for the synthetic fuel production exists in the energy system, it can significantly improve the integration of intermittent renewable energy sources as it can utilize the electricity generated in time when there is no other demand for it. The latter means that the technology can be used for effective demand-response management of electricity. Moreover, in the time with the lower electricity demand, it is natural to assume that the price of electricity will be low, following the supply and demand law. In order to assess the impact of electricity price on the total cost of synthetic fuel production, CAPEX (capital expenses) and OPEX (operating expenses), including the electricity costs, need to be assessed. Following the costs for DME production using the SOEC co-electrolysis (efficiency anticipated in 2020 65%) and syngas synthesis (efficiency today 71%) as calculated and reported in [66], a Fig. 3 was created.

On top of the costs presented in Fig. 3, the cost of electricity needs to be added. Price of electricity on a day-ahead market varies a lot. For the year 2015, in the DK-west node of Nordpool day ahead el-spot market the average spot price was 22.9 €/MWh, peak price 99.77 €/MWh and the trough price -31.41 €/MWh [109]. If one considers that the system would have excess capacity for production of synthetic fuels, it would be only used when the electricity is cheap. The lowest third of the el-spot prices for the year 2015 yields the average price of 11.31 €/MWh, peak price 19.19 €/MWh and the trough price -31.41 €/MWh. Recalculating the units and adding the average electricity price of 11.31 €/MWh yields the total price of generating a synthetic DME fuel of 64.84 €/GJ in 2015.

A significant barrier to this technology is a very small total efficiency. Efficiency of power-to-DME is 46% today and burning the fuel in the engine with approximate efficiency of 25% would lead to the total efficiency of only 11.5%. Even if arguing that synthetic fuels produced from renewable energy are CO_2 neutral, such a small efficiency is still a significant constraint for the future energy system.

If the current market structure remains in the future, the push of intermittent renewable energy sources will cause even larger number of hours with extremely high power production, which will not be followed by the high demand in the same period. It is out of the scope of this paper to discuss about the exact development of power prices in the future; the question that this paper will tackle is whether the falling prices of PVs can lead to the periods with extremely low electricity price which can then be used for the synthetic fuel production.

3.3.4.1. PV price drop. The PVs' price has tremendously dropped starting from 1970s. Crystalline silicon solar cell prices have fallen from 76.67 \$/W in 1977 to 0.74 \$/W in 2013 [110]. As there is no real constraint for mass production of PVs, it is expected that the price of PV systems will decrease even further. International Energy Agency (IEA) assumes the turnkey price in 2050 of 0.4 €/W [111] while study performed by Fraunhofer institute led to the price estimates between 0.28 and 0.61 €/W [112].

This low price of the PVs will probably cause a rapid penetration of it in the future, which will cause a significant increase of the critical

excess in electricity production (CEEP), the amount of electricity that is produced but there is no demand for it in the real time.

One potential transition scenario to 100% renewable EU has been assessed as a part of the Smart Energy Europe study [63]. The study was carried out using EnergyPLAN modelling tool and it showed that the synthetic fuels are needed as the last step if the successful transition wants to be achieved. However, in this study only the modest amount of electricity generation from PVs was assumed, equal to 7.8% of the total electricity generation, while the assumed price of the technology used was 0.9 €/W. The whole study and the underlying model, as well as the modelling tool can be freely downloaded [68].

As the authors of this paper argued that the future PV price will be much lower than the 0.9 €/W, as discussed above, a significantly larger PV penetration level in the system can be expected. Hence, the authors of this paper used the case study, the model and the modelling tool as reported in [63] as a starting point for assessing the impact of lower PV price assumption on its economically feasible penetration level.

This study adopted the PV installation price of 0.4 €/W, as anticipated by the IEA, and used this number as input in the model developed as a part of Smart Energy Europe study (all other inputs remained the same as in the original study). PV penetration level was increasing with the 10% steps, starting from the level used in the Smart Energy Europe study and the total system costs were tracked for each change in PV capacity.

Fig. 4 shows that with the increase of the installed capacity of PVs, the total system cost drops significantly, while the CEEP increases by more than a factor of 2. There are two options of dealing with the excess electricity generation from renewable sources if there is no demand for it. The first one is to curtail the generation of electricity of intermittent renewable energy sources or to utilize this excess electricity generation by some flexible demand-response technology. In the latter case generation of synthetic fuels is a viable option, as the storage for the synthetic fuels is relatively cheap due to its ability to utilize already existing storage for liquid fuels. Furthermore, this electricity could be priced at near zero value, as otherwise it would be wasted (curtailed).

Electrofuels production utilizing intermittent renewable energy sources such as PV has a significant potential for integration of power and transport sectors. Potentially large amounts of cheap electricity in certain periods of time could drive down the running costs of electrofuels production. Furthermore, if the production of electrofuels will be decentralized, it could further enhance the local economic perspectives, on top of the local economic benefits provided by a more significant penetration of PV systems. However, there are still technology issues that need to be addressed, such as the lifetime of stacks during frequent ramping up and down of electrolyzers and the efficiency of the SOEC itself. Moreover, air quality issues from utilizing electrofuels in ICEs could still be an issue in the densely populated cities, which needs to be thoroughly addressed in a systematic future research. Hence, in order to model all the mentioned points, electrofuels production needs to be modelled as a part of the whole energy system, in order to capture the interactions between intermittent sources rapidly decreasing in their price and demand for fuels in transport sector.

To sum up, Table 5 presents a qualitative assessment of the pros and cons of different technologies considered in this paper.

4. Discussion

Following the methods presented in the second section and results in the third section, several important issues can be discussed upon.

First, due to the high energy efficiency, possibility of integrating power and transport sectors, cleaner air and the reduction of CO₂ emissions, all the transport means that can be directly electrified should undergo this transition. There is no better alternative to this transition in energy terms and it is the first goal and the crucial target

that should be achieved when modelling the sustainable future transportation system. On the other hand, a rapid electrification promoted by the authors raises up different security questions in terms of heavy dependency of the transport sector on the power grid. Different emergency scenarios for cases of natural disasters, such as floods or earthquakes, should be carried out in order to locate the critical points in security of technical systems and to assess the consequences on the society in general. Certainly, modelling of the security of supply will become more complex in the future as more interactions among different energy sectors will need to be taken into consideration.

Second, the transport sector should be assessed in the context together with the expected changes in the EU28 population growth, GDP growth, increase in the share of urban population and the expected rise in transport demand in different transport modes. In a business-as-usual scenario, majority of the future transport demand will occur intra-cities, its share in total energy consumption is expected to grow, as both passengers will travel more (connected with the leisure and business time) and more goods will be transported due to the expected GDP growth. Several facts need to be stated in order to support the latter statement: urban population of the EU28 is expected to grow from 75% to 85% by 2050 [113], the EU28 total population is expected to grow from today's 508 million inhabitants to 518.8 million in 2030 (2.1%) and 525.5 million in 2050 (3.4%) (around 0.1% per annum) [114]. Moreover, depending on the economic development pathway, the total GDP will be 19.5–30.5% higher in 2030 and 41.4–53.8% higher in 2050, according to the European Commission [115]. Expected annual growth of different transportation modes can be seen in Table 6, representing an overall growth of 44.7% in passenger-km and 89.6% in ton-km.

The projected yearly rise rate of 2.1% in the aviation transport mode is especially worrisome (keeping in mind its relatively large share in total transport energy demand of 14%), recalling the difficulties with the utilization of alternative fuels in this transport mode. Moreover, a bit newer research on the future air transport demand made by International Air Transport Association (IATA) forecasts 3.8% average annual increase in the number of air passenger journeys over the next 20 years, meaning that the number of journeys in 2034 will be 2.1 times higher than today [116]. However, that growth is predicted to be 2.4% in Europe, slightly more compared to the growth rate presented in Table 6. On the positive side, in terms of energy production, the growth in the air traffic will be compensated to some extent by the increased energy efficiency in that sector. The World Bank set the goal of achieving a global increase in the aviation fuel efficiency of 2% per annum by 2050 [117]. Finally, ever rising growth of tourism will need to be dealt with in the research on future transport transition, incorporating its specific demand in both travels to the destination and within the target destination. According to [118], there are 10 main drivers of growth in the transport demand and one of the main drivers is tourism. Travel and tourism industry today represent 9.8% of global GDP and it is forecasted to grow by 4% each year over the next

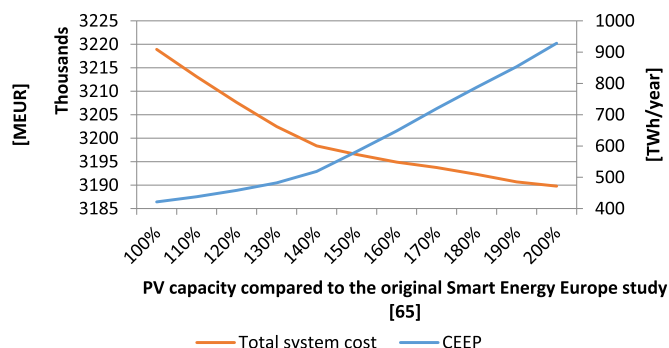


Fig. 4. Total system costs and CEEP values with the increase of installed capacity of PVs.

Table 5

Qualitative assessment of pros and cons of different alternatives.

	Economic barriers				Infrastructure barriers			
	High new infrastructure costs	High production costs	Low production efficiency	Influencing food price	Need new fuelling infrastructure	Need new supply chain	High land demand/ Sustainability problem	Intermittency friendly
Hydrogen	Yes ^{***}	Yes	Yes/No ^{**}	No	Yes	Yes	No	Yes [*]
Biofuels	No	No	No	Yes	No	No	Yes	No
Synthetic fuels	No	Yes	Yes	No	No	No	No	Yes [*]
PV for synthetic fuels	No	No	Yes	No	No	No	No	Yes

^{*} If having excess production capacity in the system and produced using electricity from RES.^{**} Low efficiency of the complete cycle (well-to-wheel).^{***} In case of distributed production of hydrogen, existing power grid would be used removing the need for completely new hydrogen infrastructure.**Table 6**

Annual growth in the transport demand in different transport modes in the period 2005–2050 [3].

	Road	Rail	Marine	Air	Total
Passenger	0.6%	2.7%	–	2.1%	0.8%
Freight	1.3%	2.3%	1.5%/2.0% ^a	–	1.4%

^a within the EU/outside the EU.

10 years on a global scale [119]. This will have a significant impact on the transport demand, especially in the aviation sector.

Third, due to the still inadequate capacity and low energy density of batteries that are built into electric vehicles, the weight of vehicles when installing batteries with larger capacities significantly increases. Consequently, light vehicles frequently used for very long distances, a part of medium weight vehicles and majority of heavy weight vehicles cannot be directly electrified. Similarly, the aircraft mode is significantly impacted by the low energy density of current batteries and it is hard to foresee large commercial planes driven by electricity stored in the chemical form of energy in batteries. Hence, four different alternatives for these modes were evaluated and the results were presented in the former section.

Fourth, although a significant increase in the energy efficiency is achieved in the part of the transport that can be directly electrified, there is still a significant demand for fossil fuels that needs to be dealt with, i.e. 1125 TWh. Producing this amount of biofuels, as described in scenario 1, leads to the biomass demand of 3069 TWh (11,048 PJ). In the second scenario, the demand for biomass was 1279 TWh.

Sustainable potential of biomass was estimated in many different reports on the EU level. The European Commission estimated sustainable wood potential to be maximally 1698 TWh, provided that an intensive wood mobilisation efforts are applied [120]. The Biomass Energy Europe project compared more than 70 biomass potential assessments and they concluded that the biomass potential in different assessments varies considerably [121]. The mean reported constrained technical potential of the biomass at the EU level is around 3000 TWh. Finally, in [122], the estimated current biomass potential from agriculture was between 0.8 and 3.9 EJ (222 and 1083 TWh) and biomass potential from forests between 0.8 and 6 EJ (222 and 1667 TWh). Although the forest biomass potential is considered to be stable over time, the agriculture biomass potential could increase in the future. Taking mean values from the latter reference gives us the total potential of biomass for energy of 1600 TWh. Mean forecasted potential for the year 2050 from the same study is equal to 2360 TWh.

The European Commission reports that between 60–70% of the annual increment of the EU forests is harvested today, which means that there is only 30–40% of available biomass for further utilization. Having these numbers in mind, it is clear that there is not enough

sustainable biomass resources for converting remaining part of the transportation sector to be driven by biofuels. Even the 1125 TWh of biomass demand for the second scenario would be extremely hard to meet in the sustainable way, as it would mean that all the non-harvested biomass potential of the future should be directed to the transportation sector. However, this is in collusion with the planners of power and heat sectors which also assume utilizing great amounts of the sustainable biomass potential in power and heat sectors.

This turns the discussion to the potential of synthetic fuels. Calculated increase in the demand for heat and electricity was 925 TWh and 2775 TWh, respectively. To have the sense of the amount of the additional energy needed, it is worth mentioning that the electricity demand in the entire EU in 2013 was 3100 TWh [123]. Hence, to meet the additional demand for generation of synthetic fuels, electricity generation in the EU should more than double. Here one needs to keep in mind that besides 2004 TWh of electricity demand for synthetic fuels, there is an additional demand for electricity of 880 TWh for the part of the transport sector that can be directly electrified. Even for the second scenario, in which the remaining part of the fossil fuels is replaced one part by biofuels and one part by synthetic fuels, the additional demand of 1646 TWh for electricity is challenging to meet. It is important to mention here that the heat energy demand for SOECs is a high-temperature one (between 700 °C and 800 °C). If high-temperature waste heat from some industrial processes would not be available, the share of energy demanded in a form of heat would also be generated from electricity, increasing the electricity demand even more.

A significant drop in PV price could have an indirect effect on the economy of synthetic fuels. Taking into a consideration the near zero electricity price in the time when there is a lack of demand for it, as shown in Fig. 4, as well as the drop of the technology costs for the production of synthetic fuels as calculated in [66], the expected cost of producing DME could be calculated to 38 €/GJ of fuel. A Gross price of one litre of diesel fuel is currently around 1.2 €/litre across the Europe. Using the lower heating value content of the diesel fuel of 39 MJ/l the calculated cost of the fuel for the end-consumer is 30.8 €/GJ, not including the negative health externalities. Hence, the production of synthetic fuels in the future could be cost competitive with the conventional fuels today, although historically it was proven to be extremely hard to forecast the tendency of the fossil fuel prices.

It is important to keep in mind that the direct cost for the end-consumer is not the only valid indicator for the energy system. Synthetic fuels allow the energy system to be more flexible as it can integrate different energy sectors, such as power, heating and gas sectors. Hence, there could be savings achieved in the energy system which cannot be directly valued as a part of the savings in fuel price.

Converting all the non-electrified parts of the transportation sector to hydrogen fuelled one can be extremely costly as well as questionable

in terms of security. Infrastructure for hydrogen driven transportation sector should be built from scratch, as well as the whole supply chain on the global level. However, the latter consideration could be opposed by production of hydrogen in a distributed way using electrolysis. In this way, energy would be transferred using existing power grid, reducing the need for building a completely new infrastructure. Furthermore, it could foster local development, as opposed to the current large-scale remote drilling and refining stations used in the oil industry.

Furthermore, a lack of research focusing on the overall transport sector on a large geographical area and its interactions with other energy sectors has been detected. One of the more recent research papers dealt with the role of transport in the Smart Energy Systems framework [124]. According to the mentioned study, a solution for the transport sector are renewable electro-fuels produced from biomass and/or concentrated CO₂. However, two points need to be discussed upon. First, their calculated sustainable biomass consumption was 13.72 EJ/year (3810 TWh/year), which is possibly an overestimated value, based on the references presented in this study. The authors of this paper are of the opinion that due to the significant uncertainties in different studies on biomass potential, lower values of uncertainty region shall be used for energy planning. Second, the authors mentioned enormous capacity increase needed to reach their goals, i.e. 2750 GW of offshore wind, 900 GW onshore wind and 700 GW of PVs shall be installed by 2050 [124]. These totals in 4350 GW of needed capacity which is more than a fourfold increase compared to the currently installed capacity, being less than 1000 GW [125]. Hence, the authors of this paper would like to emphasize the latter point, which is in line with the very large energy requirements calculated for the alternatives in this paper, and argue that it will be highly complicated to reach the needed capacities. Furthermore, the needed capacities would be even larger, if one would adopt biomass potential argued in this paper.

Hence, the authors are of the position that the possibility of the transition of the transport sector's part that cannot be directly electrified could be found in emerging technologies, which would increase the efficiency of the transport sector, as opposed to the concept of synthetic fuels and/or renewable electrofuels which cause an increase in energy consumption overall. In total, seven promising emerging alternatives were detected in the literature review: delivery drones that could increase efficiencies along the commercial supply chains [126], public transportation combined with car hailing and car sharing possibilities [127], 3D printing that could allow distributed manufacturing processes, reducing the need for transporting manufactured parts [128], hydrogen in aviation such as zeppelins, some of which are being currently prototyped [129], catenary vehicles that could use electricity directly, without the need for large batteries [130], inductive charging, also reducing the need for large batteries [131] and Hyperloops, extremely high speed vehicles operating in specialized low-pressure tubes [132]. All the mentioned alternatives could significantly increase transport efficiency, avoiding the emissions in the first place. The authors would like to invite researchers to contribute more time towards assessing the potential of these technologies on the overall energy system.

Furthermore, as the urban population is expected to grow in the future, air pollution, especially in large cities, is a growing problem that has gained more attention recently [133]. Especially worrisome pollutant from the cars are NO_x emissions, as well as PM_{2.5} in a lesser manner [135]. Considering this aspect, it is important to emphasize that combustion of synthetic fuels, renewable electrofuels and/or biofuels still produce NO_x emissions and PM_{2.5}, even if the CO₂ emissions would be argued as neutral, impacting the quality of life, especially in cities. According to the IEA, around 6.5 million deaths worldwide are attributed to the air pollution, much greater than the HIV/AIDS, tuberculosis and road injuries combined, being the 4th largest threat to the human health [133]. Hence, the authors argue

that, already being very complex to carry out transition towards renewable transport sector, a future research should incorporate considerations about air quality in order to encompass both sustainable and renewable aspects of the future transport sector.

The literature review presented in the introduction section detected that most of the research focused on single sector solutions, or even focused on single technologies, such as electric cars. Some research for marine transport and/or aviation transport sectors was also carried out independently of the impact on the whole energy system, adding to the conclusion that there is currently a lack of systematic studies taking into account the transition in the transport sector and its impact on the other energy sectors. This study confirmed the importance of the holistic view when modelling transport sector and detected that, after the energy efficiency benefits achieved by directly electrifying one part of the energy sector, a significant energy resources would be needed for the final transition towards completely sustainable transport sector.

In order to address the latter and due to the ever increasing amount of emerging alternatives, with somewhat vague and ambiguous prospects, several different aspects should be taken into account in research in order to avoid ill-founded assumptions. First, the share of urban population will increase in the future, which will lead to more intra-cities transport demand, as well as raise the complexity of the transport patterns. Second, a constant rise in tourism activities will further burden the infrastructure and make the transport demand patterns less regular. Issues connected with the air pollution will be especially emphasized in ever-growing cities; hence, the harmful emission and particulate matter emitters should be reduced as much as possible. Third, enormous resources needed for the part of the transport that cannot be directly electrified by the current state of the technology development, should steer the researchers towards areas of research connected with the possibility to *reduce* or *avoid* transport demand. In order to promote the latter, a suitable approach could be to distinguish transformation in the transport sector between passenger transport and freight transport. The latter could be seriously tackled by technologies such as drone deliveries, modal shift from planes to ships or trains and 3D printing, fostering distributed production that avoids (or at least reduces) the need for transport. Passenger transport could benefit more from schemes such as increase in the public transportation presence, car hailing and car sharing schemes (as well as integration of the latter three technologies) and utilizing smart-data approach in future smart cities. The transition towards both sustainable and renewable transport sector will be neither easy nor harmless for some sectors and industries; however, prospects of cleaner, safer, sustainable and more affordable transport sector should overpower any obstacles on the way.

5. Conclusions

To sum up, several explicit conclusions can be made out of the proposed model and mapping of current transport situation and potential of renewable resources:

- ✓ All the transport means should be converted to electrified transportation modes if there is a technical possibility for it. Benefits of this transition are fourfold: reduced CO₂ emissions, increased energy efficiency, better air quality and the integration of different energy sectors.
- ✓ It is technically possible today to shift 72.3% of the fossil fuel demand in the transportation sector to the electricity. Following this transition, increased efficiency of the electrically driven transportation means will reduce the final energy demand in transportation sector for 50.6% or 2051 TWh.
- ✓ For the remaining part of the fossil fuels several alternatives exist. Due to the lower estimated well to wheel efficiency of the alternatives, a significant additional demand for resources occurs. In the case of replacement of remaining part of fossil fuels by biofuels,

additional biomass demand is equal to 3069 TWh. In the mixed scenario of biofuels and synthetic fuels additional demand for biomass, electricity and heat are 1279 TWh, 1646 TWh and 549 TWh, respectively. Finally, in the scenario with synthetic fuels used as a replacement for the remaining part of fossil fuels, additional demand for electricity and heat were 2775 TWh and 925 TWh. Additional demand for electricity in the latter scenario (including the demand of 880 TWh needed for electrified part of the transportation) is more than the total electricity demand of the whole EU in 2013.

- ✓ If the excess capacity for synthetic fuels production would exist in the system, excess electricity for which there is no demand could be utilized at the near-zero price. With the expected technology price drop until the year 2050, the price of producing DME, a potential substitute for diesel fuel, was estimated to be 38 €/GJ of fuel, which would be cost-competitive with the current end user fuel prices.
- ✓ Significant costs of building completely new infrastructure, as well as lower efficiency compared to the electric vehicles, could be too large burden for the wide scale development of the hydrogen driven transportation system, in spite of its benefits on the air pollution issue and the reduced CO₂ emissions. The Modal shift to railway transportation mode is also challenging in terms of infrastructure costs.

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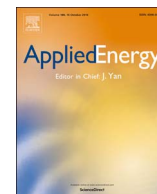
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Paper 5 - Potential of district cooling in hot and humid climates

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Potential of district cooling in hot and humid climates

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HIGHLIGHTS

- Operation of the large-scale district cooling grid was simulated.
- Proposed district cooling grid reduces CO₂ emissions and energy consumption.
- Implementation of DC grid positively impacts the economics of the energy system.
- Singapore was chosen for a case study that represents hot and humid climates.
- The model is well suited for the other countries in the region.

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Scenario modeling

ABSTRACT

Efficiently utilizing energy that is currently being wasted can significantly increase energy efficiency of the system, as well as reduce the carbon footprint. In hot climates with large cooling demands, excess waste heat can be utilized via absorption chillers to generate cold. Moreover, cold from liquefied natural gas gasification process can further provide energy source for meeting the cold demand. In order to connect the large sources of waste heat and cold energy with customers demanding the cold, a significant investment in district cooling grid is a necessity. In order to deal with the mentioned issue, an existing energy balance model was complemented with Matlab algorithms in order to model the whole energy system, including the detailed representation of the district cooling grid. Singapore was chosen for a case study and several different scenarios were developed for the year 2050, with the main indicators being total primary energy supply, total CO₂ emissions and total socio-economic costs. The most beneficial scenario for the year 2050 had 19.5% lower primary energy demand, 38.4% lower total socio-economic costs and 41.5% lower CO₂ emissions compared to the business-as-usual scenario for the year 2050, although significant investment in the district cooling grid was included in the calculations.

1. Introduction

Climate change is impacting the Earth, posing a threat to sustainable development of different regions. Though agreement was reached during the COP21 [1] and COP22 [2] conferences in Paris and Marrakech, resulting in a now legally binding agreement upon curbing the CO₂ emissions, harmful consequences of climate change cannot be avoided and mitigation measures need to be adopted. Furthermore, rapid urbanization is taking place and it is expected that two thirds of world population will live in cities by the year 2050, increasing the complexity of energy supply [3]. Some regions will urbanize more rapidly than the others, presenting the need to detect the most efficient

energy solutions early, in order to avoid a lock-in effect of investing in inefficient infrastructure [4].

Around the tropics, climate is dominated by humid air and high temperatures throughout the year, causing large energy demand for decreasing air temperature and dehumidifying the air [5]. Large and relatively constant energy demand for cooling throughout the year can be met by different sources. Although in more moderate climates heat sinks are better researched, either in terms of free cooling of rivers and lakes or in combination with chillers, there is a lack of possible heat sinks in regions being close to the thermodynamic equilibrium, where the climate is being dominated by small temperature differences of the air, ground and sea during the year [5]. The potential of ground source

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Nomenclature

Term	Remarks, units		
WH_i	yearly waste heat potential of the i -th considered plant, kWh	$E_{supply,t}$	power that needed to be supplied in each hour in order to satisfy the final energy demand in each hour and losses of the transmission and distribution grids, kW
η_{total}	total potential efficiency of the plant, kWh _{output} /kWh _{fuel}	c_p	specific heat of water, 4.187 kJ/(kg K)
$\eta_{electrical}$	electrical efficiency of the plant, kWh _e /kWh _{fuel}	U	overall heat transfer coefficient, W/(m ² K)
$F_{fuel,i}$	yearly consumed fuel energy in the considered plant, kWh	A	area of the pipe surface,
$C_{supply,LNG}$	cold extracted from LNG gasification process, kWh	ΔT_1	temperature difference between the water flowing inside the pipes and the ground on the outer wall of the piping, K
LNG	amount of liquefied natural gas imported, kg	l	length of the considered pipe section, m
$C_{supply,i}$	cold potential of the i -th considered plant, kWh	r	radius of the pipe section, m
$C_{supply,total}$	total cold potential in the considered area, kWh	Q	volume flow inside the pipe section, m ³ /s
A_{cool}	total buildings area that needs to be cooled down,	ρ	density of water 1000 kg/m ³
PR_i	plot ratio of the i -th land plot, m ² /m ²	f_D	darcy friction factor, –
$A_{land,i}$	i -th land plot area,	v	velocity of the flow, m/s
C_{demand}	yearly cooling energy demand per m ² of the considered area, kWh/m ²	ΔT_2	temperature difference between supply and return line of the DC network, K
EUI_i	energy use intensity, kWh/(m ² * year)	\dot{m}	mass flow inside pipe section, kg/s
T_{loss}	thermal losses in the grid, kW	l_i	length of the each pipe section, m
P_{loss}	power needed to overcome the pressure losses in the grid, kW	P_i	price per meter of each pipe section, USD/m

heat pump in western Singapore was assessed in [6]. The main detected benefits were potential reduction of heat island effect by removing cooling towers and reduced water consumption [6]. However, the authors of the paper acknowledged unfavorable ground conditions in Singapore and concluded that the latter is the main reason for relatively low electricity consumption reduction [6]. Bruelisauer et al. analyzed ground, seas, river and air temperatures of Singapore and concluded that they are not suitable sources for free cooling in any of the seasons during the year [5]. Hence, alternative cooling sources need to be selected for meeting the cooling energy needs.

Cooling demand can be met focusing on individual solutions or focusing on one solution for the whole building, cluster of buildings or the whole districts. Individual solutions usually involve air-conditioning split systems, technically called air-to-air heat pumps. In the tropical region, for the general cooling energy needs of buildings, split systems usually achieve coefficient of performance (COP) in the range of 2.5–3.25, electric chillers with dry air cooling tower achieve COP in the range of 3.5–5 and electric chillers with wet cooling tower achieve COP in the range of 6–10 [5].

Compared to individual split systems, more efficient solutions can be done using absorption or electric chillers. An absorption chiller uses waste heat at temperatures around 90–95 °C [7], while electricity is needed only for pumping the working fluid. Therefore, it is possible to expect total plant electrical efficiency ratio (EER) of 15–25, while thermal energy efficiency for single effect absorption units is typically 0.7 [8]. In order to be able to utilize absorption chillers, one must have steadily available streams of waste heat as otherwise electric chillers would be more viable. It was shown that despite the advances of electrically driven chillers, utilization of absorption chillers leads to the cost-effective CO₂ emission reduction, if there is availability of cheap excess heat [9]. Further research on upgrading cogeneration to tri-generation systems was presented in [10]. The authors showed that the tri-generation is beneficial for the northern European countries; however, they have pointed out that it would be very interesting to apply their research to tropical regions, where more steady demand for cooling occurs throughout the year [10].

One of suitable sources for district cooling is liquefied natural gas (LNG) regasification. In an advanced liquefaction process, about 2900 kJ/kg of energy is consumed; 2070 kJ/kg being dissipated as heat and 830 kJ/kg (0.23 kWh/kg of LNG) being stored in LNG as cold [11]. However, due to the cryogenic temperature of LNG, released cold is also suitable for air separation, material freezing, dry ice production and

refrigeration in chemical industry. Thus, several solutions can compete for the same resource. According to the available literature, LNG cold from regasification can be utilized for air separation, power generation, cold storage and dry ice production, as well as for district cooling [12]. A very successful example of utilization of cold energy from LNG gasification is a cascade process developed at Osaka LNG terminal [13]. They have combined ethylene plant, air separation, carbon dioxide liquefaction, water chilling and the expansion turbine in order to utilize the cold, achieving exergy efficiency of 52% [13].

In tropics, although there is often a lot of waste heat available from industry and different energy plants, there is usually a lack of demand for it, as the temperatures are high throughout the year. Hence, in hot and humid climates, a district cooling grid is one of the potential solutions for distributing the waste energy in the form of cold to the customers. Although focusing only on municipal waste incineration plants as a potential heat source in tropical urban areas, researchers showed on the case of Thailand that absorption chillers are capable of introducing significant savings in the energy system, by reducing the electricity demand for compression chillers [14].

Most of the past large district cooling research projects, in terms of number of case studies, were carried out or are currently undergoing in Europe, where cooling demand is less steady and highly seasonal in comparison with tropical regions. The most significant project that was finished is the Rescue project [15], funded by the EU. Other important projects are Stratego [16] and International Energy Agency's advocated case study on district cooling in Stockholm [17]. The Rescue report advocates that the first step should be the identification of all possible sources of natural cooling and the second step should be locating the waste heat potential [15]. The Stratego report argued that the optimal level of district cooling is still unclear and recommended more research to be carried out towards the design of the district cooling network [16]. On the other hand, the largest projects on district cooling in terms of capacity took place in Qatar, Kuwait and United Arab Emirates. In Qatar, the district cooling plant at The Pearl-Qatar has the combined cooling power of 450 MW and it seems to be the world's largest integrated district cooling plant so far [18]. In Kuwait, the Shadadiyah University's campus will be cooled with 36 electric chillers with the combined cooling power of 252 MW [19]. However, the latter two projects are lacking of systematic scientific research on the operation of the systems. District cooling system was proposed for the South East Kowloon Development project in Hong Kong and the authors concluded that the proposed district cooling system for the region was feasible,

except the cold storage that was not profitable according to the existed financial conditions [20]. The proposed system was later developed and achieved energy savings were 20–35% compared to the air conditioning split systems and decentralized chillers [21]. The designed capacity of 284 MW will result in annual electricity saving of 85 GWh, equivalent to the CO₂ reduction of 59.5 ktons [21].

In Iskandar, Malaysia, a new industrial park is being built in phases. The electricity demand is expected to be met by the combined-cycle gas turbine with the electric output of 45 MW [22]. The pre-feasibility study of the district cooling in the area proposes to utilize waste heat from the gas power plants (PP) to drive absorption chillers in order to provide the cold in the industry park [22]. One of the largest district cooling networks is located in central Singapore and it is cooling the Marina Bay district [23]. The combined chiller capacity of two plants is 157 MW of cooling energy with the possibility to extend the capacity in the coming years [23]. Cold is being produced by electric chillers, while ice thermal storage with the discharge rate of 30 MW is installed to optimize the cold supply. Finally, the authors in [24] mentioned waste heat from different energy plants that could be used for district cooling in the tropical region. However, their proposed “cooling highways” were not their core aim of the research; hence, transmission and distribution grids were not calculated thoroughly and there is a lack of exact quantitative results that could be used for estimation of the pros and cons of large district cooling systems.

The presented literature review shows that the majority of systematic research was carried out in Europe with other climate patterns than in the tropics. Some district cooling projects, focusing on specific energy sources, were carried out in the South-east Asia; however, DC was not researched on a system scale, missing the consequences that DC can have on other energy sectors, such as the power sector. As there is no country in tropical region that has adopted DC on a wide scale so far, there is a need to research the potential of widely adopted DC in regions with steady cooling demand, in order to assess the interactions between different energy sectors, its impact on energy demand and CO₂ emissions. Finally, modeling costs of establishing such systematic networks, as well as dimensioning it, was not the part of any previous research known to the authors.

Thus, in order to address the latter research gap, the aim of this paper is to address the feasibility of utilizing waste heat for cold and LNG cooling sources at a high rate, systematically developing the DC network. Second, comparison of the socio-economic costs of the system with high penetration of DC versus the business-as-usual system is another goal of the paper. Third, existing model for hourly energy balancing should be expanded with more detailed DC algorithms in order to allow for robust dimensioning of the DC network, avoiding potential pitfalls in estimation of DC grid installation costs. Besides the methods adopted, a further novelty in this paper is the choice of case study, i.e., the high population density country, with 100% urbanization rate [25] and with steady cooling energy demand throughout the whole year, as opposed to cases where cooling demand has seasonal patterns and free cooling energy is sometimes available. The latter consideration makes the model suitable for consideration in other tropical regions, too.

The introduction section of this paper is followed by methods section in which detailed explanation of the combination of already existing energy balancing model EnergyPLAN and the Matlab algorithms developed for representing DC grid is provided. Case study and scenario development is the following section that provides a description of the case study used to prove the hypothesis and fill the detected research gaps. Resulting investment in the district cooling grid, thermal and mechanical losses, as well as the socio-economic and environmental findings are presented in the Results section. The paper ends with the discussion section, in which the results are discussed in the holistic manner, and the conclusions section, in which the main quantitative results are clearly stated.

2. Methods

The developed methods consisted of four steps that were carried out in order to achieve robust results:

- (1) Locating potential sources of energy and calculating cold potential.
- (2) Calculating cooling energy demand of the considered area for utilization of district cooling potential.
- (3) Establishing initial grid layout, calculating cold flows, heat and pressure losses in the grid and establishing piping diameters needed to meet the peak cooling energy demand.
- (4) Calculating socio-economic costs of different scenarios utilizing district cooling energy and comparison with business-as-usual (BAU) scenario.

2.1. Locating potential sources of energy and calculating cold potential

This step consisted of locating the major gas PPs, waste incineration plants and LNG gasification terminal and estimating the waste heat potential. Waste heat potential was estimated using Eq. (1)

$$WH_i = (\eta_{total} - \eta_{electrical}) \cdot Fuel_i \quad (1)$$

where WH_i presents yearly waste heat potential of the i -th considered plant, η_{total} total potential efficiency of the plant obtained from different references, $\eta_{electrical}$ real electrical efficiency of the plant and $Fuel_i$ yearly consumed fuel energy in the considered plant.

Total efficiency of the plant η_{total} is defined as the ratio of the total useful combined heat and power output and the fuel input, while electrical efficiency $\eta_{electrical}$ is defined as the ratio of the useful power output and the fuel input. Cold derived from LNG gasification was calculated using Eq. (2)

$$C_{supply,LNG} = 0.23 \cdot LNG \quad (2)$$

Recall that the cold content in liquefied natural gas is 0.23 kWh/kg [11], while LNG presents the amount of liquefied natural gas imported [kg]. $C_{supply,LNG}$ presents the cold extracted from LNG gasification process.

Potential cold production, at the locations where waste heat is available, was estimated using the obtained waste heat potentials from Eq. (1) and multiplying it with the COP value of the single phase LiBr-water absorption chillers, as presented in Eq. (3). The most common COP value used in references was 0.7 [7,8,26].

$$C_{supply,i} = WH_i \cdot 0.7 \quad (3)$$

where $C_{supply,i}$ presents cold potential of the i -th considered plant.

$$C_{supply,total} = C_{supply,LNG} + \sum C_{supply,i} \quad (4)$$

In Eq. (4), $C_{supply,total}$ presents the total cold potential in the considered area.

2.2. Calculating cooling energy demand of considered area for utilization of district cooling potential

Initial grid layout should be constructed using the official cadastral plan or master plan or any other similar document. In the cadastral plan, plot ratios are stated for each land plot and area of each land plot can be calculated using different GIS tools. Plot ratio is the ratio of maximally allowed gross floor area (GFA) to land area. Using Eq. (5), the area that needs to be cooled is estimated.

$$A_{cool} = \sum_{i=1}^n PR_i \cdot A_{land,i} \quad (5)$$

where A_{cool} is total buildings area that needs to be cooled down, PR_i is plot ratio of the i -th land plot and $A_{land,i}$ is i -th land plot area.

Energy Use Intensity (EUI) in kWh/(m² * year) for cooling purposes

should be extracted from available references and differentiated between the commercial and residential sectors. Using Eq. (6) the final cooling energy demand can be calculated for the considered area.

$$C_{demand} = \sum_{i=1}^n PR_i \cdot A_{land,i} \cdot EUI_i \quad (6)$$

where C_{demand} is yearly cooling energy demand per m^2 of the considered area.

2.3. Establishing initial grid layout, calculating cold flows, heat and pressure losses in the grid and establishing piping diameters needed to meet the peak cooling energy demand

The grid layout (transmission and distribution pipes) should be constructed following the layout of the roads as it is considered that this would be economically feasible way for installing DC pipes. Upon initial consideration of the grid layout, mass flows in each piping branch can be calculated taking into account thermal and pressure losses. Results of this part of methods are pipe diameters, needed for the estimation of investment in the DC grid, and losses that occur in the grid, needed to be able to calculate the final delivered energy.

$$E_{supply,t} = C_{demand,t} + T_{loss} + P_{loss} \quad (7)$$

where T_{loss} represents thermal losses in the grid, P_{loss} power needed to overcome the pressure losses in the grid, while $E_{supply,t}$ is cold power that needed to be supplied in each hour in order to satisfy the final energy demand and losses of the transmission and distribution grids.

$$T_{loss} = U \cdot A \cdot \Delta T_1 \quad (8)$$

where U represents overall heat transfer coefficient, A is the area of the pipe surface and ΔT_1 represents temperature difference between the water flowing inside the pipes and ground on the outer wall of the piping. A is calculated using Eq. (9):

$$A = 2 \cdot \pi \cdot r \cdot l \quad (9)$$

where l is the length of the considered pipe section and r radius of the pipe section. The assumption made is one-dimensional heat conduction through the uninsulated pipes. Power needed to overcome the pressure loss is estimated using Eqs. (10) and (11):

$$P_{loss} = Q \cdot \rho \cdot g \cdot f_D \cdot \frac{l}{2 \cdot r} \cdot \frac{v^2}{2g} \quad (10)$$

where Q is the volume flow rate inside the pipe section, ρ density of water, f_D Darcy friction factor and v velocity of the flow.

$$Q = v \cdot r^2 \cdot \pi \quad (11)$$

Cold power needed to meet final energy demand, as well as to overcome the losses in the grid, can also be expressed using Eq. (12):

$$E_{supply,t} = \dot{m} \cdot c_p \cdot \Delta T_2 \quad (12)$$

where ΔT_2 represents temperature difference between supply and return line of the DC network, while mass flow rate \dot{m} can be expressed using Eq. (13):

$$\dot{m} = \rho \cdot v \cdot r^2 \cdot \pi \quad (13)$$

By combining Eqs. (7)–(13) and restructuring the terms, the quadratic equation can be obtained:

$$r^2(\rho \cdot v \cdot \pi) - r \left(2 \cdot U \cdot \pi \cdot l \cdot \Delta T_1 + v^3 \cdot \pi \cdot \rho \cdot f_D \cdot \frac{l}{4} \right) - C_{demand} = 0 \quad (14)$$

In Eq. (14), only radius r of the each pipe section is unknown, while other terms were predetermined using the values obtained from the literature.

$$Cost = \sum_{i=1}^n l_i \cdot P_i \quad (15)$$

The total cost of the DC grid is represented by Eq. (15), where l_i represents the length of the each pipe section and P_i the price per meter of each pipe section. It is of utmost importance to bear in mind that P_i depends on the piping radius.

2.4. Calculating socio-economic costs of different scenarios utilizing district cooling energy and comparison with business-as-usual (BAU) scenario

The cost of the district cooling grid calculated from Eq. (15) was input for the EnergyPLAN model. The latter modeling tool was used in order to model the systematic effects that district cooling has on the whole energy system. EnergyPLAN is a simulation tool that is used for modeling energy systems, especially suitable for modeling systems with high share of the intermittent power, as it simulates the energy system during one year on hourly resolution [27]. It follows the concept of smart energy systems, in which synergies detected between power, heat/cold, gas and mobility sectors are utilized in order to develop cheaper sustainable energy system. The detailed comparison between TIMES/MARKAL optimization family of models and EnergyPLAN simulation tool was carried out in [28], while comparison of numerous different energy modeling tools, with the emphasize on those suitable for modeling the renewable energy systems, was presented in [29]. A detailed description of the pros and cons of the EnergyPLAN model was carried out in [30]. The EnergyPLAN model was used for many case studies with the large share of renewable energy systems on different geographical scales. It was used for modeling: regions, such as EU28 [31], countries, such as Ireland [32], cities, such as Copenhagen [33] and islands, such as Mljet [34].

Outputs of the EnergyPLAN model are total energy system costs including fixed, variable and levelized investment costs, CO₂ emissions, primary energy supply,¹ hourly generation of each modeled technology during the year, storage balances, etc.

For the purpose of this model, socio-economic costs included levelized investment costs during the lifetime of each modeled technology, fixed and variable operating and maintenance costs (O & M), fuel costs and new infrastructure costs such as an investment in district cooling grid. They were calculated using Eqs. (16) and (17) [27].

$$Cost = \sum_{i=1}^n (fixO \& M_i + lev_{inv_i})x_i + \sum_{j=1}^m \left(varO \& M_j + \frac{fuel_j}{\eta_j} + CO_{2j} \cdot CO_{2intenj} \right) x_j \quad (16)$$

where

$$lev_{inv_i} = inv_i \cdot \frac{disrate_i}{1 - (1 + disrate_i)^{-lifetime_i}} \quad (17)$$

where $fixO \& M_i$ represents fixed O & M cost (USD/MW), lev_{inv_i} annualized investment cost of a specific technology (USD/MW), inv_i total investment cost (USD), $disrate_i$ real discount rate (%), $lifetime_i$ expected lifetime of the plant (years), $varO \& M_j$ variable O & M cost (USD/MWh), $fuel_j$ and η_j fuel consumption (MWh) and efficiency of the specific technology (MWh/MWh), while CO_{2j} and $CO_{2intenj}$ represent the cost of CO₂ emissions (USD/tCO₂) and CO₂ intensity of a specific technology (tCO₂/MWh). Finally, x_i present capacity variables of different technologies i (MW), while x_j represents generation variables (MWh) of those technologies. All the economic values are in real terms, meaning that they are inflation-adjusted during the future years.

Opposite to the business-economic costs, socio-economic costs do not incorporate taxes as they are considered to be internally redistributed income (within the area). On the other hand, the CO₂ tax is not

¹ Primary energy supply (equal to the primary energy demand) is defined as the total energy supply/demand in its crude form, without being subjected to any conversion process.

Table 1
Overview of different scenarios.

	Reference scenario (REF)	Business as usual (BAU)	District cooling (DC)	District cooling and increased PV penetration (DC-PV)	Increased PV penetration (PV)
Year	2014	2050			
Features	Developed using official statistics from different sources	Scenarios representing normal development of the system with no major incentives for change	BAU + the implementation of district cooling system	BAU + DC + rapid penetration of PV systems	BAU + rapid penetration of PV systems

a classical “business tax” as it represents internalized negative externality in terms of climate change costs. Hence, carbon tax was included in the total socio-economic costs.

3. Case study and scenario development

In order to validate the developed model and to assess the impact of district cooling on the holistically modeled energy system, a case study that represents the hot and humid climate was carried out. Singapore was chosen for a case study. Singapore is located only 142 km north from equator and thus it can successfully represent a tropical region. It is also economically developed country with high cooling energy demand. Finally, the large amount of data available to model the energy system, as well as the availability of future plans, makes it suitable for developing the robust case study.

3.1. Overview of the case study and scenarios

Singapore is a 100% urbanized country [25], located in the tropical region in South-east Asia. It has a population of 5.54 million, covering the land area of only 719 km². It has a tropical climate, with steady high temperatures, with outdoor temperatures ranging from 24.5 °C to 31.2 °C during the year [35]. According to the World Bank, in 2015 it had GDP at power purchase parity of 80,192 USD in constant 2011 prices, the 3rd highest in the world [36].

Currently, Singapore is producing more than 95% of her electricity from imported gas [37]. In 2014, 337,372 TJ of natural gas and 94,588 TJ of LNG were imported [37]. Thus, the share of LNG in total gas consumption was 21.9% and it is expected to rise in the coming years. Its regasification terminal is located in the south west of the country, having the capacity of around 3 million tons of LNG per annum.

Possible major sources of waste heat in Singapore can be found in industry, especially petrochemical industry [8], waste incineration plants and gas-driven power plants (PPs). There are four operating gas PPs in Singapore, all of them being located on Jurong island in the south west of the country. Two of them utilize waste heat and feed it to the industry in the form of steam. Moreover, most of the electricity that is not produced from gas PPs is generated from waste incineration plants. Currently, there are four waste incineration plants, three of them being located in the Tuas (south-west part of the country) and one of them in the north of the country in the Woodlands district. Presently, they are only generating electricity and they are not using waste heat for any process. Highly efficient combined cycle gas PPs can have electrical efficiency of 60% [38], while total heat utilization of the waste incineration plant in Malaysia was reported at 80% [39]. Combining the data with the reported efficiencies of the Danish technological report [40] shows that a significant amount of waste heat can be utilized from these plants. Although significant amount of waste heat from energy plants is not being utilized currently in Singapore, one can note that all the waste heat comes from several highly concentrated sources.

Concerning the EUI, the value of 215 kWh/m² per annum for the commercial sector and the value of 55 kWh/m² per annum for the residential sector was adopted [41,42]. The carbon tax in Singapore

should start from the 2019 and it is expected to be in the range of 7.15–14.3 USD/tCO₂ [43]. The European Commission issued a report stating expected increase in the CO₂ emission allowances in the EU until the year 2050 [44]. Using the same relative increase in CO₂ price as EU assumed, and the starting price of 10.7 USD/tCO₂ for the year 2019, a carbon tax of 65 USD/tCO₂ was obtained for the year 2050.

EnergyPLAN model was used for developing all the scenarios; reference one for the year 2014 and four scenarios for the year 2050: business-as-usual (BAU), district cooling (DC), district cooling and increased photovoltaics (DC-PV) and increased photovoltaics with no district cooling (PV). The overview of different scenarios can be seen in Table 1.

3.2. Reference scenario

In order to validate the model, a reference scenario (REF) for the year 2014 was developed. Energy supply and demand data were obtained from the International Energy Agency [45] and Singapore's Energy Market Authority [37]. Final energy demand is divided into three sectors in EnergyPLAN: Individual, Industry and Transport, while electricity demand distribution is common and encompasses electricity consumption in all the sectors except electrified mobility. Final energy demand data used for the reference year can be seen in Table 2.

There are currently four gas driven PPs operating in Singapore, all being located on Jurong Island. Furthermore, there are four waste incineration plants, three being located in Tuas area and one in Woodlands area. Total capacities can be seen in Table 3.

As Singapore is geographically constrained and has only limited energy resources, it imported a significant amount of fuels to meet its needs in 2014. It imported 162 Mtoe of energy products in 2014, mostly crude oil and petroleum products, and exported 86 Mtoe of energy products, mostly petroleum products due to its strong refining sector [37]. Total import of natural gas was 10.3 Mtoe, 22% in the form of liquefied natural gas and the rest via the gas pipeline [37]. More than 95% of electricity was generated from gas PPs, while the major share of

Table 2
Final energy demand in the reference year.

Name	2014 [TWh]	Ref.
Electricity demand	49.31	[45]
Individual heating demand	2.81	[45]
Industry fuel demand	69.77	[45]
Transport fuel demand	25.31	[45]

Table 3
Energy supply of Singapore in the reference scenario.

Plant type	Capacity [MW]	Fuel	Efficiency	Refs.
Power plants	2225	Natural gas/LNG	47.5%	[37,46]
Waste-to-energy plants	256.8	Waste	16.7%	[37,45,46]
PV	33.1	–	12.4% (capacity factor)	[37,45]

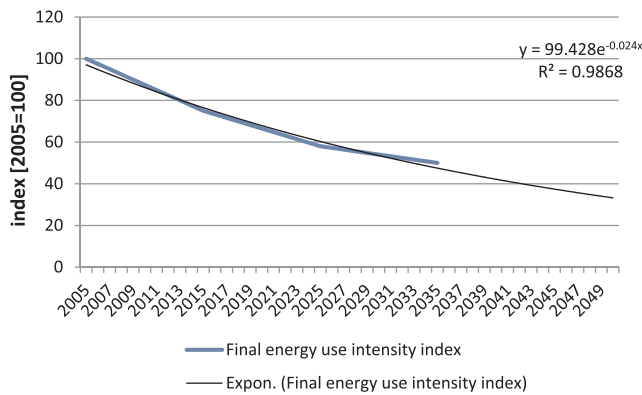


Fig. 1. Final energy use intensity index - projected values (2005 = 100).

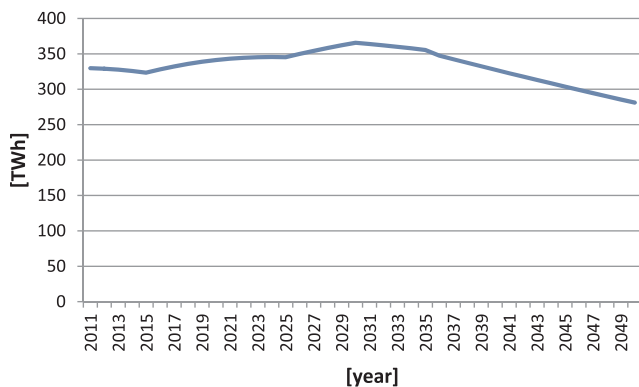


Fig. 2. Total primary energy demand projection.

the remaining part of the power generation had waste incineration plants [37].

According to the IEA's statistics, the total primary energy supply was 28.01 Mtoe, while CO₂ emissions were 45.32 Mt. Hourly electricity demand distribution was obtained from Singapore's Energy Market Authority, while the hourly solar irradiation was obtained from Meteornorm software. Hourly cooling load profiles were obtained from [47,48] and scaled according to the share of each building type's energy consumption [37].

3.3. Business-as-usual scenario

Business-as-usual (BAU) scenario was made for the year 2050. It includes only general policies and economic development without adopting any measures that could boost development of certain technologies or energy sectors. Singapore's population is projected to be 6,680,000 in 2050 [49], while nominal GDP is projected to be 526.1 billion 2010 USD [50]. Singapore's energy intensity up to 2035 was projected in [51] while the energy intensity in 2050 was obtained extrapolating the historical data and projection up until 2035. The obtained energy intensity time series can be seen in Fig. 1.

Combining the population growth data, GDP forecast and energy intensity index, one can obtain total primary energy demand projection up to the year 2050, as presented in Fig. 2.

Thus, the total primary energy supply in the BAU scenario for the year 2050 was estimated to be 281.1 TWh. The share of energy sector consumption to the total energy consumption was modeled to be at the same level as in the reference year. Hence, the total primary energy supply of the energy sector (i.e. consumption that is modeled in EnergyPLAN) was 174.1 TWh in the BAU scenario.

The amount of cold energy available from the LNG gasification terminal was calculated using the Singapore's statistics on LNG imports [37]. Furthermore, it was taken into account that the annual average

growth rate of LNG import between 2016 and 2025 is expected to be 10.39% [52], as well as that the total capacity of gasification terminal is expected to be 9 million tons per annum [53]. In order to calculate the cold potential from gasification for the year 2050, the same average yearly growth rate was extrapolated until the year 2030, after which it was held constant. If the demand for gas in the energy system in specific scenario was lower than the capacity of the gasification terminal, the total demand for gas was used as the amount of LNG import in a specific year. For the year 2050, it was assumed that all the natural gas consumed was imported in the form of LNG.

In order to successfully represent a district cooling system and all its interactions with other parts of energy system, it is important to properly model developments of different energy sectors. For the purpose of this paper, most of the expected policies in other sectors were obtained from the official technology roadmaps carried out for CCS, PVs, Green Data Centers, Building Energy Efficiency, Industry Energy Efficiency, Waste Management and E-Mobility. Different research pathways were presented for research, development, demonstration and deployment of the specific technologies. Sector data that were taken from these studies encompasses PV penetration, electric vehicles penetration, expected energy efficiency measures in buildings, industry and power sector [54–57] and the exact figures are presented in Table 4. More specifically, Solar Photovoltaic Roadmap for Singapore presented two main scenarios for future development of PVs in Singapore, the Baseline scenario (BAS) and Accelerated scenario (ACC). The accelerated scenario assumed larger utilization areas for PVs, accelerated growth in PV efficiency and yield and accelerated cost reduction of the technology [54]. Industry Energy Efficiency Technology Roadmap showed a great potential for energy efficiency gains until the year 2030. It assessed five key areas and the technical potential of energy efficiency gains was 5.7% until the year 2030, while additional 13.1% of energy savings could be achieved if best available technologies would be deployed [55]. Electro mobility roadmap presented three different electrification scenario of the transport sector. One of the conclusions claims that in the High Scenario, EVs could bring down emissions from the transport sector by 64% compared to the BAU in 2050 [56]. Furthermore, the roadmap presented for potential scenarios for regulated increase of the number of vehicles, dubbed S1–S4 [56]. In the most beneficial scenario (S4), the number of vehicles in the year 2050 will be the same as in the year 2020 and increase by 2.7% from 2015 to 2020, while in the least beneficial scenario (S1) the number of vehicles in the year 2050 will be 9.1% larger than in the year 2015 [56]. Finally, Building Energy Efficiency R & D Roadmap formulated a list of 52 technologies that need to be developed in order to significantly contribute to the increased energy efficiency in Singapore's building sector [57]. It was calculated that the latter sector alone could cumulatively reduce 22–28% of CO₂ emissions until the year 2030 compared to the BAU scenario [57]. All the roadmaps are freely available on Singapore's National Climate Change Secretariat's website [58].

Furthermore, it was assumed that 90% of the electric vehicles will be connected to Smart Charge system and 10% to Dumb Charge system by the year 2050 (all scenarios) in order to alleviate potentially high peak demands in certain periods of time. Smart Charge system corresponds to the charging according to the present power source and demand situation in the system. Utilizing this option, the system aims for finding the cheapest way of charging the vehicles; e.g., when excess electricity from intermittent sources is available. On the other hand, dumb charge corresponds to the uncontrolled charging of the vehicles straight upon the plug-in of the vehicles.

3.4. Alternative scenarios

Alternative scenarios for the year 2050 include PV, DC and DC-PV scenarios, as described in Table 1. In DC and DC-PV scenarios, district cooling demand, being able to cover all the losses occurred in the

distribution grid, was calculated using Eq. (7), while cooling demand was estimated using Eq. (6). Locations chosen to be suitable for a shift towards district cooling were those that are closer to the waste heat sources. Although there are not many references in the literature for the maximum distance of cold supply, there are examples of operating district heating systems with distances of 20 km, such as in Hamburg, Germany, or 30 km, which is the case between Roskilde and Copenhagen, Denmark [63]. As the temperature difference between cooling medium flowing inside the piping and the surrounding ground temperature, and accompanied energy losses, is much smaller in district cooling grids than in district heating grids, at least the same distances should be feasible in the case of district cooling. The furthest point of cold delivery of the district cooling grid from energy sources in this case study was approximately 20 km.

Geographic Information Systems (GIS) mapping of the transmission and distribution piping was determined using the URA SPACE integrated map portal [64]. Plot ratios were taken from Singapore's 2014 master plan [65]. Detailed representation of the proposed transmission and distribution sections used in calculations are graphically represented in Appendix 1. Overview of the data presented in Appendix 1 can be seen in Table 5.

One can notice that proposed district cooling system in the South-west part of Singapore would be significantly larger than in the Northern part as a consequence of larger energy supply for cold generation being available in the South-west part.

Major sources of potential waste heat, as well as LNG gasification terminal can be seen in Fig. 3.

Potential capacity of the PV systems in PV and DC-PV scenarios was calculated updating the assumptions found in the Solar roadmap for Singapore [54]. The authors of the roadmap stated that they have used very conservative estimations of the available area for PV installation. Using less conservative estimations and taking into account the fact that many cooling towers for electric chillers on the rooftops can be avoided using the district cooling system, a net usable area for PV installations was estimated to be 74.4 km², as it can be seen in Table 6.

Finally, fuel prices projections for the year 2050 were taken from the US Energy Information Administration [66]. The majority of the technology capital costs, variable and fixed operating and maintenance

Table 5

Summary of the data presented in Appendix 1.

	Total transmission piping length [km]	Total distribution piping length [km]	Total floor area to be cooled [km ²]
Woodlands (Northern part)	1.34	4.68	3.64
South-west part	78.69	91.3	146.4

costs were taken from [27], while the exceptions were PV costs, taken from [54], and DC infrastructure costs, taken from [67].

4. Results

4.1. Investment, dimensioning and the operational consideration of district cooling grid

Cooling energy generation was simulated during one week in June and the total cooling energy demand and cooling energy supply, as well as the total investment in infrastructure can be seen in Table 7. Northern and South-west part of Singapore were modeled for cold demand, as it can be seen from Fig. 3 that these geographical areas are the closest to the potential major waste heat and LNG cold sources. Hence, in these areas the installation costs of the transmission and distribution networks will be the lowest.

As Singapore has steady weekly cold demand throughout the whole year, the yearly cooling demand values were calculated by multiplication of the values obtained for the simulated week with the number of weeks in a year.

Initial grid layout was constructed using the official cadastral plan (called the master plan) of the Singapore's Urban Redevelopment Authority (URA) [68]. In the cadastral plan, plot ratios are stated for each land plot and areas of each land plot were calculated using available website tools. Plot ratio is the ratio of maximally allowed gross floor area (GFA) to land area. Calculated cold supply potential C_{supply} in the South-west part includes potential from two out of four gas

Table 4

Adopted figures in different scenarios developed for the year 2050 and corresponding references.

	Statement from the reference	BAU	DC	DC-PV	PV	Ref.
Electric vehicles penetration	Different scenarios; "High" scenario from the [56] assumes that 54% could be BEVs and 12% PHEVs in the year 2050	40% of the total energy demand for transport	63% ^a of the total energy demand for transport	63% ^a of transport energy demand	63% ^a of transport energy demand	[56]
Efficiency in transportation	S4 scenario from [56] – 0.25% vehicle population increase till 2020, 0% afterwards (till 2050)	0.25% vehicle population increase till 2020, 0% afterwards (till 2050)				[56]
PV penetration	15 TWh in the accelerated scenario 7 TWh in the baseline scenario	7 TWh	14.7 TWh	32 TWh	32 TWh	[54]
Energy efficiency in power sector	E3 scenario from [54] would mean 50 TWh of final energy demand for electricity due to the strong energy efficiency efforts	50 TWh of final energy demand for electricity ^b				[54]
PV technological development	PV η = 28% ^c technical lifetime = 40 yearsfull cost (baseline sc) = 0.70 USD/W ^d	Adopted statements from the reference without alterations				[54]
Energy efficiency in buildings	Efficiency measures reflected in final energy demand for electricity that equals 50 TWh					[57]
Energy efficiency in industry	Efficiency measures reflected in final energy demand for electricity that equals 50 TWh; In DC, DC-PV and PV scenarios all coal consumption and 75% of oil consumption is shifted to natural gas consumption by the year 2050					[55]

^a Assumption derived from the "high" scenario in Ref. [56] for the year 2050.

^b This number does not include possible further reduction in demand for electricity due to the switch from electric heat pumps to district cooling.

^c The possible PV efficiency development was also assessed in [59]. The reported expected efficiency for mono-crystalline photovoltaic cell for the year 2027 was 26%.

^d Relatively low cost assumed for the target year 2050 can also be found in [60], where a discussion on PV price was carried out and the price of 0.47 USD/W was adopted. Furthermore, Fraunhofer Institute had estimated a price range of PV in 2050 between 0.33–0.71 USD/W [61], while International Energy Agency forecasted a price at 0.47 USD/W [62].

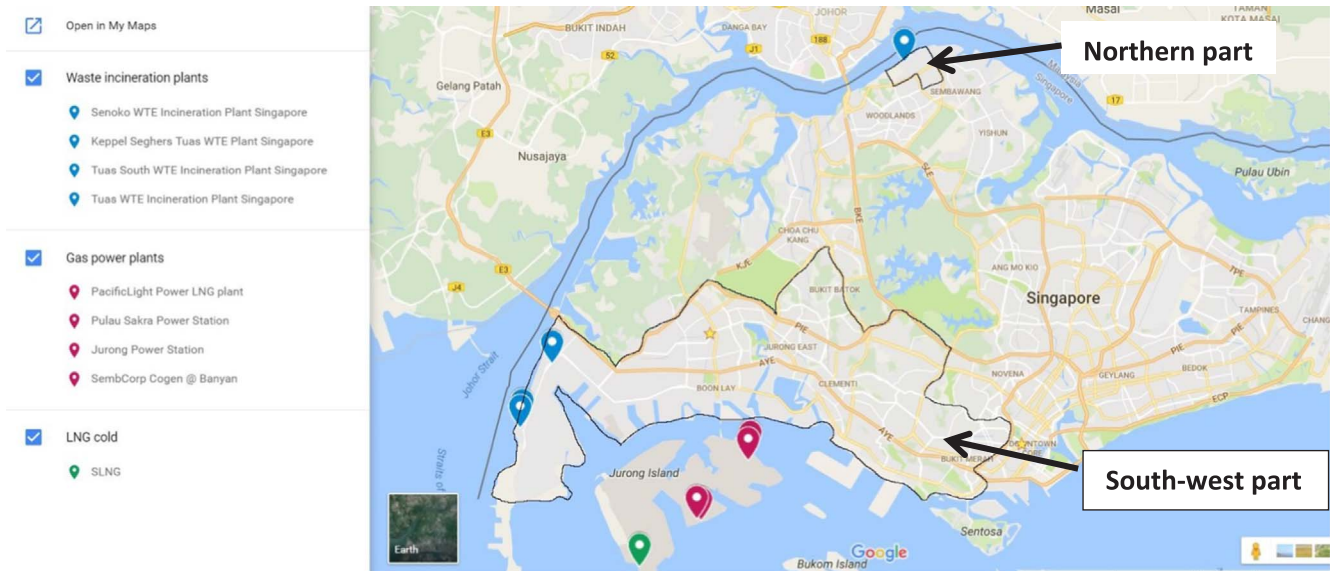


Fig. 3. Locations of major waste heat sources, cold from LNG gasification terminal and the modeled areas (designated with black boundaries) for district cooling in DC and DC-PV scenarios (Map data ©2017 Google).

PPs (as other two gas plants are already supplying waste heat to the industry), three waste incineration plants located in that part of the island and the LNG gasification terminal. It can be seen from the Table 7 that the simulated cooling energy demand E_{supply} is lower than the potential C_{supply} in the both areas. Thus, the assumed district cooling system is technically viable.

There were in total 54 transmission pipe sections and 61 distribution pipe sections modeled for the South-west part of Singapore and four transmission and five distribution sections for the northern part of Singapore (Woodlands). Resulting radii of each pipe section needed to be sufficient to transfer the sufficient amount of cooling energy, covering both thermal and mechanical losses of the grid, taking into account that the maximum possible ΔT_2 was set to 13 K.

For the northern part of Singapore, resulting transmission pipe radii were between 0.36 m and 0.71 m while the distribution pipes radii were between 0.19 m and 0.64 m. During the simulated week, the total grid losses account for 5.7% of the cold supply to the grid. Out of the total losses 19% occurred as mechanical losses and 81% as thermal losses. Changing cooling demands in different hours was met by changing temperature difference in the supply network, keeping the mass flow constant. Detailed scheme of the grid in both geographical areas can be seen in the Appendix 1, while the detailed numerical results can be assessed in the Appendix 2.

For the South-west part of Singapore, resulting transmission pipe radii were between 0.16 m and 1.94 m while the distribution pipe radii were in the range of 0.06–0.8 m. It should be noted here that pipe diameters above 0.7 m would be constructed as two or more parallel pipes instead of very large diameters of a single pipe. The total losses in the South-west part were equal to 4.76%. The share of mechanical losses was 18.3% and the share of thermal losses was 81.7%. Detailed

Table 7
Simulated weekly and calculated yearly cooling energy demand.

	C_{demand} [GWh] - weekly	C_{demand} [GWh] - yearly	E_{supply} [GWh] - weekly	E_{supply} [GWh] - yearly	C_{supply} [GWh] - yearly	Grid cost [mil USD]
Northern part	15.01	782.6	15.80	823.9	1238	8
South-west part	322.07	16793.5	338.17	17633.2	21,609	331

results of piping dimensioning, thermal and mechanical losses in each hour during the modeled week and the temperature differences in each hour can be seen in detail in Appendix 2.

Overview of the main results of Appendix 2 can be seen in Table 8. Taking into account obtained radii and length of each pipe section, using equation (15) and adopting values P_i (the cost of installing piping per unit of length, as a function of the pipe radius) from [67], the total investment in district cooling grid was calculated. The total investment cost of the northern part of Singapore amounted to 8 million USD, while the total investment cost in the South-west part of Singapore totaled to 331 million USD. These investment cost were leveled over the period of 30 years using a discount rate of 4%. Yearly operating and maintenance costs were set to 3% of the total investment.

4.2. Reference scenario and model validation

A comparison of the total primary energy supply and CO₂ emissions obtained for the reference year (2014) in EnergyPLAN modeling tool

Table 6
Calculate net usable area for PV installations.

	Area utilization factor	Conservative net-usable area from [54] [km ²]	Net usable area after population rise is taken into account [km ²]	New area utilization factor	Net usable area after less conservative approach is taken [km ²]
Rooftop area	0.5 and 0.6	34	43.83	0.9	60.23
Facades	0.4	4	5.16	0.6	7.16
Infrastructure	1	0.5	0.5		0.5
Islets	0.05	2.5	2.5		2.5
Inland waters	4	4	4		4
Total		45	56		74.4

Table 8

Overview of the results presented in Appendix 2.

	Woodlands (Northern part)	South-west part
Minimum transmission pipe radius [m]	0.365	0.164
Maximum transmission pipe radius [m]	0.716	1.943
Average transmission pipe radius [m]	0.607	1.048
Minimum distribution pipe radius [m]	0.193	0.064
Maximum distribution pipe radius [m]	0.636	0.795
Average distribution pipe radius [m]	0.341	0.309
Total weekly pressure losses [GWh]	0.18	2.95
Total weekly thermal losses [GWh]	0.75	13.16
Maximum delta T [K]	12.83	12.68
Minimum delta T [K]	0.00	1.32
Average delta T [K]	4.14	8.20

Table 9

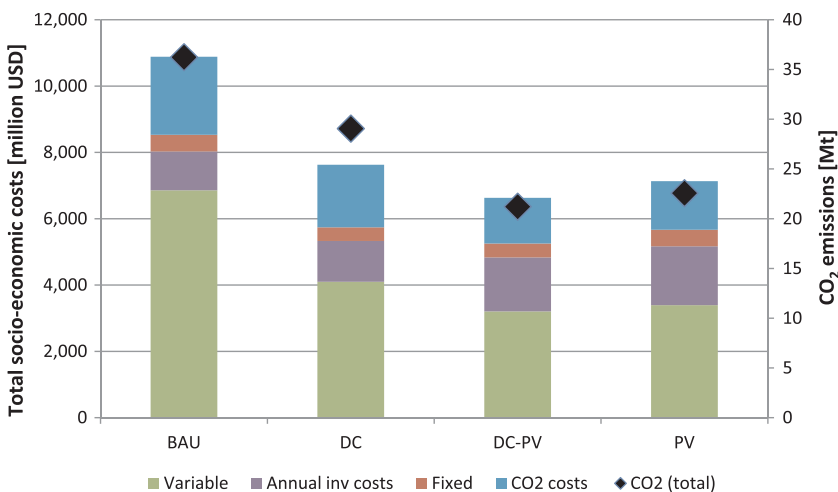
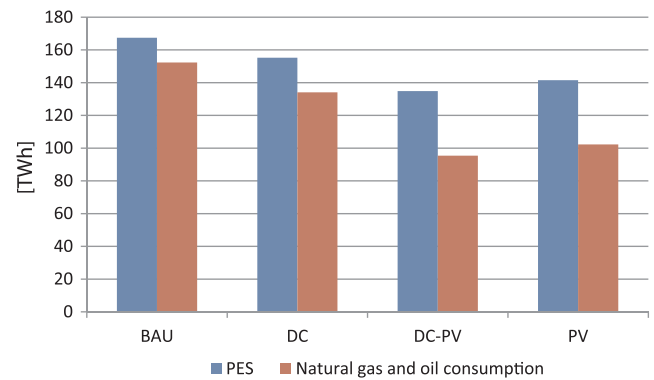
Comparison of reference scenario in EnergyPLAN and official values.

	Reference scenario (REF)	IEA [45]	Difference
Coal consumption	4.63	4.6	0.28%
Gas consumption	109.07	106.9	1.95%
Oil consumption ^a		206.2	
Oil consumption - only combustion	85.93	82.5	4.02%
Primary Energy Supply ^a		325.8	
Primary Energy Supply (only combustion)	207.73	202.1	2.71%
CO ₂ emissions	46.857	45.32	3.28%

^a IEA includes oil consumption used in petrochemical industry for production of different products that have no accompanied CO₂ emissions. In EnergyPLAN this part of the primary energy supply is not modeled; only the primary energy demand for combustion purposes, which produce CO₂ emissions, could be modeled.

and values obtained from International Energy Agency's website for Singapore [45] can be seen in Table 9.

It can be noted from Table 9 that the difference between official data and the data obtained from the simulation do not exceed 5% for any of the fuels or CO₂ emissions. Hence, it was concluded that the model can be used for modeling future energy scenarios of Singapore.

**Fig. 4.** Economic and environmental results of different scenarios for the year 2050.**Fig. 5.** Primary energy supply and fossil fuel consumption in different scenarios.

4.3. Scenarios for the year 2050

Total socio-economic costs and CO₂ emissions for the BAU and alternative scenarios for the year 2050 can be seen in Fig. 4. The largest costs occurred in BAU scenario (10,884 mil USD), followed by DC (7628 mil USD), PV (7133 mil USD) and DC-PV (6631 mil USD) scenarios. Scenarios lower in total socio-economic costs had also lower CO₂ emissions. The CO₂ emissions in BAU, DC, PV and DC-PV scenarios were 36.23, 29.06, 22.57 and 21.21 Mt, respectively. One can note also that the variable costs in the BAU scenarios are much larger than in alternative scenarios, making alternative scenarios less volatile and less prone to changes in import prices of the fuels.

The total primary energy supply and gas consumption in different scenarios can be seen in Fig. 5.

Primary energy supply in the DC and PV scenarios was 7.3% and 15.5% lower than in BAU scenario. The largest PES reduction occurred in DC-PV scenario; its PES was a significant 19.5% lower than in BAU scenario. DC-PV scenario also showed that the optimal level (that minimizes the total socio-economic cost of the energy system) of centrally installed electric chillers was 89 MW_e, and the optimal capacity of cold storage was 7.7 GWh_c. Due to the serious scarcity of land in Singapore, ice-storage was assumed to be used in order to utilize the latent heat of ice, lowering the needed volume for the storage. The ice cold storage with the capacity of 7.7 GWh_c would have a volume of 90,536 m³.

In order to assess the behavior of selected technologies in the simulated energy system, an excerpt from the simulation results for the DC scenario is shown in Fig. 6.

It can be seen from Fig. 6 that the centralized electric chillers are operating when there is a significant generation of electricity from PVs. In that way, electricity with a low marginal cost of generation can be

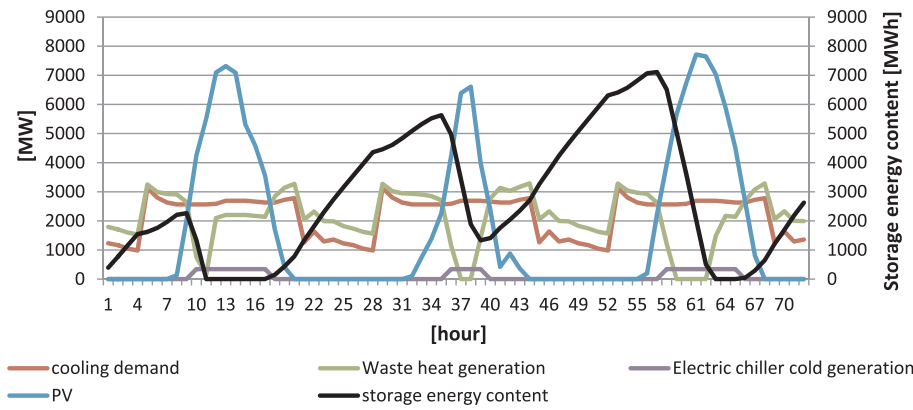


Fig. 6. Operation of different selected technologies in the DC scenario during the first three days of the year 2050.

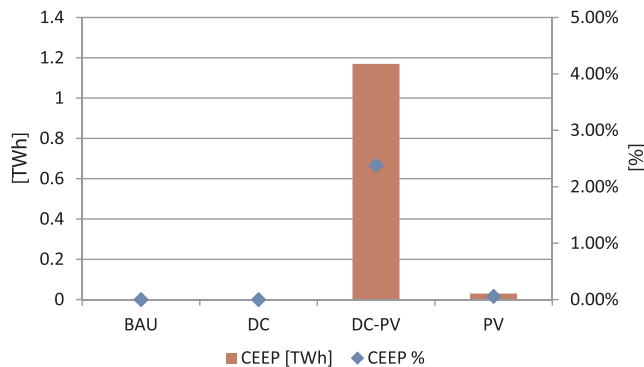


Fig. 7. CEEP in absolute and relative amounts in different scenarios for the year 2050.

utilized to produce cold in an efficient way, reducing also the potential of having the excess electricity generation during the peak PV output. Furthermore, it can be noted that the waste heat generation will drop during the maximum output from PVs, as PVs are able to meet the total electricity demand in those periods (and no electricity and heat generation are needed from gas CHPs and waste incineration plants). On the other hand, except the electric chillers, cold storage is the technology that can help meeting the cold demand in periods when there is a lack of waste heat generation that could be utilized in absorption chillers. In periods when there is an excess in waste heat generation, cold can be stored for later periods. In this way, cold storage, electric chillers, PVs, CHPs and waste incineration plants can successfully integrate power and heat/cold sectors, utilizing a cheaper ice cold storage compared to the battery storage.

One of the negative consequences of large share of intermittent renewable energy in the energy system is the occurrence of periods when the generated electricity exceeds the demand for it, wasting electricity that could have been generated for a low marginal cost. EnergyPLAN software introduced Critical Excess in Electricity Production parameter (CEEP). The CEEP is the amount of electricity that is generated but cannot be exported or utilized as there is not enough demand. The energy system is technically solid, and renewable energy sources are successfully integrated, if the CEEP does not exceed 5% of the total electricity generation. The CEEP indicator in both absolute and relative terms is presented in Fig. 7.

The share of CEEP was well below the 5% target, which shows that large amount of intermittent can be successfully integrated in the energy system of Singapore. Following the implementation of the assumptions presented in the Table 4, the resulting share of renewable energy sources in power generation was 70.6% in DC-PV and 64.8% in PV scenarios. A successful integration of these large amounts of intermittent renewables was possible due to the electrification of a part of the transport and utilizing the V2G concept, as well as the utilization of cold storage that is cheaper compared to battery storage. By combining

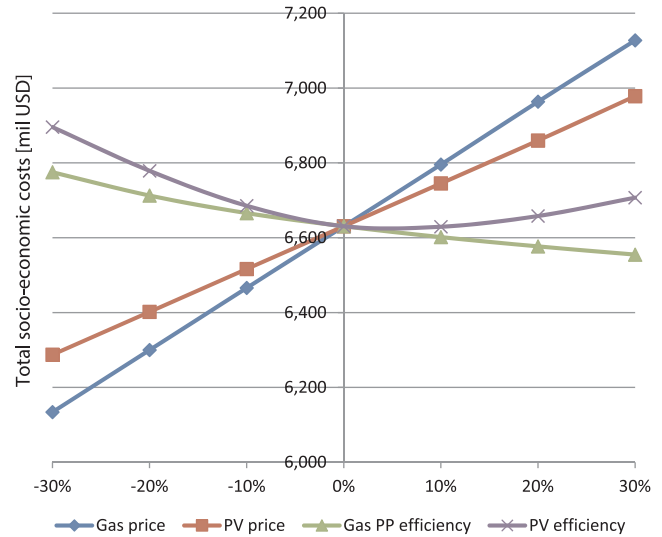


Fig. 8. The impact of different variables on total socio-economic costs.

the electric chillers in the periods of low demand and/or high electricity generation, one can produce cold and store it in the cold storage for later use in the district cooling network.

4.4. Sensitivity analysis

In order to check the robustness of the results, a sensitivity analysis was carried out. The analysis was carried out for DC-PV scenario and the influences of gas price, PV panels price, gas PP efficiency and PV efficiency on the total socio-economic costs and CO₂ emissions were assessed. The impact of the four mentioned variables on the total socio-economic costs can be seen in Fig. 8. One can note that the gas price has the most significant impact on the total socio-economic costs, i.e., an increase of gas price of 30% will increase the total socio-economic costs for 7.5%. An increase in the price of PV panels of 30% will result in a 5.2% larger total socio-economic cost. Very interesting behavior can be seen in PV efficiency variable. As a land in Singapore is scarce, there is a fixed amount of space where PV panels can be installed. Having lower efficiency than expected, less capacity of panels will be possible to install, which causes larger total socio-economic costs because of the more fossil fuel demand. On the other hand, exceeding the panel efficiency by more than 10% will also cause larger total socio-economic costs. The latter can be explained by already large share of the electricity generated from the PV in the DC-PV scenario. Further increase in the installed PV panels causes more and more excess electricity generation which cannot be consumed and thus, installation costs of additional PVs cannot be recuperated by savings in fossil fuel and CO₂ payments.

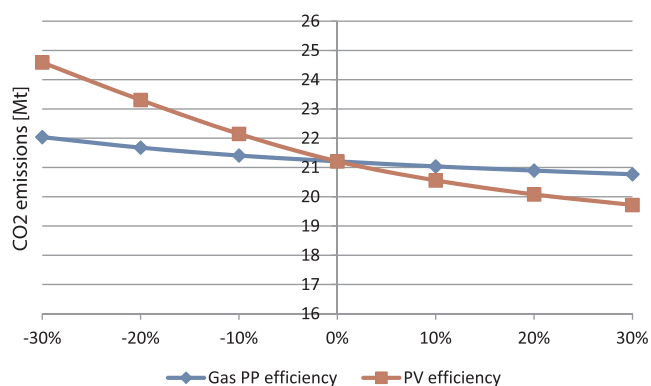


Fig. 9. The impact of different variables on total CO₂ emissions.

The impact of gas PP efficiency and PV efficiency on the CO₂ emitted can be seen in Fig. 9. PV efficiency has much larger influence than the gas PP efficiency and the decrease of 30% in PV efficiency would increase CO₂ emissions for 15.9%.

On the other hand, the increase of PV efficiency for 30% would result in 7.02% lower CO₂ emissions. The latter is caused by already large penetration of electricity generated from PVs and a large share of the additionally generated electricity would not be consumed (the PV production would be curbed) due to the mismatch in timing of electricity generation and demand. Relatively low reduction of CO₂ emissions in the case of 30% larger gas PP efficiency, i.e. 2.1% lower CO₂ emissions, is mainly the result of low generation share of electricity generated from gas driven plants in DC-PV scenario, i.e. 29.4%.

5. Discussion

The results of this paper show that there is a significant potential of waste heat that can be utilized via absorption chillers to produce cold. However, due to the nature of the sources, which are highly concentrated at few sites, a district cooling network needs to be established in order to connect the customers demanding the cooling energy with energy sources. The resulting calculation of the district cooling grid showed that the total investment of 339 million USD is offset by total socio-economic savings, making the potential future energy system of Singapore cheaper, more energy efficient and less climate harmful. The CO₂ emissions in DC-PV scenarios were 41.5% lower compared to the BAU scenario, while the total socio-economic costs were lower by 39.1%, achieved mainly by significantly reduced import of fossil fuels. Imports of gas and oil in DC-PV scenario were 37.4% lower than in BAU scenario. The latter shows that implementation of district cooling, along with the PVs, can increase the security of energy supply by reduction of import energy demand. It is interesting finding that scenarios lower in total socio-economic costs have also lower CO₂ emissions. This means that the savings in fuel costs and carbon tax payments offset the additional investment costs in the energy infrastructure.

Introducing district cooling network removes the need for having many decentralized cooling towers, usually located on the rooftops, allowing more PVs to be installed on the rooftops. Already high renewable energy share in power generation of 64.8% in the PV scenario increased even more, to 70.6% in the DC-PV scenario, while still achieving technically sound system, with CEEP indicator being significantly below the threshold of 5%.

After reaching a large share of intermittent renewable power in the energy system, further penetration of it needs to be balanced by energy storage. As there are no hills in Singapore that would be suitable for pumped hydro plant, one option could be to install electric batteries for storing the excess electricity generated. However, a cheaper option is to utilize cold storage and electric chillers in periods when there is excess of cheap electricity generated. The result of utilizing the latter

combination is that the costs in DC-PV scenarios were 7.0% lower than in PV scenario, although investments in cold storage and central electric chillers had to be taken into account.

Moreover, although it was not a subject of this paper, removing decentralized cooling towers from the densely populated areas of the city reduces the heat island effect. However, to quantify this benefit, a more detailed study should be carried out.

Compared to the more systematic studies carried out mostly in Europe, and presented in the Introduction section, a significant difference that occurs in the energy system of Singapore is the lack of any kind of energy potential, i.e., the temperature difference of the air, ground and sea is very uniform during the year and there are no mountains that could be utilized for pumped hydro storage. Hence, no free cooling sources could be utilized in this area. On the positive side, relatively steady and high temperature and humidity over the year result in a constant cooling energy demand.

Further focusing on the case study, it can be also used to support Singapore's Research, Innovation and Enterprise 2020 Plan [69]. One of the domains of the mentioned plan is the Urban Solutions and Sustainability (USS) in which it is stated that one focus to accelerate the translation of R & D to industry adoption will be Waste to Energy plant in Tuas. The findings presented in this paper about the potential for district cooling can further steer the research for successful utilization of the waste heat from Waste to Energy plants located in Singapore. However, it must be noted that the non-homogeneous operations of the Waste to Energy plants coupled with the variability of the waste heat available might affect the amount of chilled water generated by the absorption chillers; this aspect should be carefully assessed when sizing and designing the district cooling system.

Future work could further integrate water sector into holistic planning of the energy system, especially as Singapore currently uses reverse osmosis technology for water desalination that satisfies one part of the water demand of Singapore. Reverse osmosis desalination is a suitable technology for demand response measures that could further integrate intermittent renewable energy sources such as photovoltaics. Possible benefits of integration of reverse osmosis in the energy planning was presented in [65].

Finally, this study successfully showed that the implementation of district cooling system in hot and humid climate is economically sound, environmentally beneficial and a technically viable investment. Compared to the other studies presented in the Introduction section, this paper successfully quantified both costs and benefits of installing a district cooling grid, as well as its impact on the holistically modeled energy system. Finally, both thermal and mechanical losses were calculated for the proposed layout of the transmission and distribution grid. A future research should further address the concept of smart energy system, integration of different areas within the city and implementation of enhanced ICT technologies in DC systems that could introduce additional flexibility and demand response in the energy system.

6. Conclusions

There are three main conclusions that arose from the case study, which showed that district cooling systems in hot and humid climates are beneficial solution, especially in future energy systems, dominated by large shares of intermittent renewable energy sources. First, there are significant environmental benefits as the consequence of integration of district cooling in the energy system. The CO₂ emissions of Singapore's energy system were lowered by 41.5% in the year 2050 in the DC-PV scenario compared to the BAU scenario. The beneficial scenario assumed the implementation of district cooling, increased penetration of PVs, improved energy efficiency in industry and buildings and the implementation of smart charge of vehicles. Second, implementation of district cooling significantly raises efficiency of the energy system. The primary energy supply in PV and DC-PV scenarios

were 15.5% and 19.5% lower than in the BAU scenario for the year 2050. Third, implementation of district cooling can positively impact the economic side of the energy system. The total calculated investment cost in district cooling grid amounted to 339 million USD. However this cost was offset by increased energy savings in terms of fossil fuel imports. Thus, the total socio-economic costs of the energy system of Singapore in DC and DC-PV scenarios were 32.7% and 38.4% lower than in BAU scenario. Sensitivity analysis showed that the results are generally robust, while the largest influence on the total socio-economic costs had natural gas price. Concerning the CO₂ emissions, the most sensitive parameter is the anticipated efficiency of PV panels.

Compared to other studies on district cooling, this study focused on district cooling on a system scale, developing a detailed model of transmission and distribution grid feasibility. Hence, the developed model is well suited for other district cooling systems in the region. The latter could be very significant as south-east Asia is rapidly developing region, with estimated growth in energy demand of 80% until the year 2040 [4]. Having well financed R&D programs, and being economically developed country, Singapore could be a role model for implementation of district cooling systems on a large scale, as well as facilitate knowledge transfer towards other countries in the region. Finally, systematic development of district cooling grid before rapid development takes place can be beneficial measure for increasing energy efficiency of the system, as well as improve the economic feasibility of implementing the district cooling system.

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Appendices 1 and 2. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.apenergy.2017.09.052>.

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Paper 6 - On the way towards smart energy supply in cities:
The impact of interconnecting geographically distributed district
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On the way towards smart energy supply in cities: The impact of interconnecting geographically distributed district heating grids on the energy system



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ABSTRACT

A linear continuous optimization model with an hourly time resolution was developed in order to model the impact of subsequent interconnections of different DH grids. The municipality of Sønderborg was chosen for a case study and interconnections of five currently disconnected DH grids were assessed. Moreover, the impact of industrial waste heat on the DH supply was also assessed. In the reference year (2013) two out of four interconnections proved to be economically viable. The results for the future energy system (2029) showed that interconnecting geographically distributed DH grids reduces primary energy supply by 9.5%, CO₂ emissions by 11.1% and total system costs by 6.3%. Inclusion of industrial waste heat in the fully interconnected DH grid reduced primary energy supply for an additional 3%, CO₂ emissions for an additional 2.2% and total system costs for an additional 1.3%. The case of the future energy supply system with interconnected DH grids and installed industrial waste heat recuperation results in the lowest primary energy demand, emissions and costs. Finally, the benefits of the interconnected DH grid, in terms of system flexibility, CO₂ emissions, total costs and energy efficiency, proved to be much greater in the future energy system.

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1. Introduction

Worldwide, understanding the harmful consequences of climate change is receiving ever more attention. During the 2015 Paris Climate Conference (COP21), the first ever legally binding global climate deal was agreed upon, committing all the countries involved to make an impact on the climate change, starting from the year 2020. The parties agreed to keep the global temperature rise below 2 °C compared to the pre-industrial level, and aiming for the maximum increase of only 1.5 °C. Carbon neutrality is aimed for by the second half of the century [1]. Moreover, the focus of the 2016 Climate Change Conference in Marrakech (COP22) was on adopting a work plan, developing a framework for implementation and discussing possible issues of the COP21 agreement, with the

main emphasis on overcoming barriers for the agreement to become fully operational [2].

Reviewing the energy planning models available, Mancarella [3] made a comprehensive paper about the concepts and evaluation methods of multi-energy systems. The author summarized the general motion towards the integrated energy system planning, as opposed to the classical approach to energy system planning where its sectors are treated separately. Furthermore, one of the main conclusions was that the integrated energy system modelling is beneficial compared to the classical approach. The integrated energy system planning also goes by the name of “the smart energy system” approach, where the power, heat and gas sectors (including mobility) are modelled together in order to detect synergies between the sectors and achieve a cheaper and technically more robust energy system [4]. It is an especially useful approach in modelling 100% renewable energy systems. The study in Ref. [5] indicates that the holistic approach of smart energy systems, where different sectors are integrated and district heating (DH) is the major link between the heat and electricity sector in urban areas, can help to avoid large-scale integration of costly electricity storage.

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Increasing the DH share is one way of improving the energy efficiency in energy systems where a heating demand is present. Furthermore, it allows a better integration of the power and heating sectors which facilitates the integration of intermittent energy sources, such as wind power and photovoltaics. Xiong et al. [6] showed in the case of China that implementation of the scenario with the expanded DH grid could lead to the 50% reduction in the primary energy supply for the building heating sector compared to the reference case. Moreover, total system cost in the heating sector would be approximately 15% lower compared to the reference case. The EU recently released its first ever heating and cooling strategy where the European Commission argued that a strategy of decarbonising the heating and cooling sectors would save around €40 billion in gas imports and €4.9 billion in oil imports yearly [7].

Böttger et al. showed for the case of Germany that electric boilers can be a promising technology for balancing the power grid. Thus, integration of power and heating systems proved to be beneficial for the whole energy system [8]. Capuder & Mancarella argued that although there is a growing interest in the integrated energy planning approach, it is still arguable to which extent the efficiency can be improved from coupling different energy vectors [9]. They developed a synthetic mixed-integer linear optimization model suitable for evaluating the characteristics of different multi-generation options. They concluded that flexible integrated schemes with combined heat and power plants (CHP) and electric heat pumps, supported by thermal energy storage, can bring a significant operational and investment cost savings. Moghaddam et al. developed a comprehensive model for self-scheduling of an energy hub to supply cooling, heating and electrical demands of a building [10]. Although they focused on the building level of planning, they also showed the importance of integrated planning of different energy needs. One important way a future district heating system could develop in is the utilization of excess heat from industry and agriculture. This would allow increased energy efficiency in the system as less heat would be lost in industrial processes, as well as increase the competition among the DH suppliers, compared to the common monopolistic position of heat suppliers today. A regional case study of utilizing excess heat was done by Sandvall et al. for the case of Sweden [11]. Their results are not straightforward and show that from the system's point of view, CO₂ emissions only decrease in the long run, while in the short run they can even increase.

In Denmark, due to the first and second oil crises, a paradigm shift towards RES happened during the 1970s, as an effort to increase the security of energy supply. The current Danish Government set a target to phase out use of all fossil fuels and to achieve a low carbon society by 2050 [12]. As a part of the same set of policies, Denmark plans to phase out the use of all coal, as well as oil for heating purposes [13]. As a part of the policy to increase the energy efficiency, Denmark expanded its DH. Today, about 60% of the Danish heating energy demand comes from the DH. In their paper about reaching a 100% renewable energy system of Denmark in 2050, Lund & Mathiesen showed that DH will still represent a major role in meeting the heating needs [14]. The authors argued that DH systems in 2050 would consist of CHPs and boilers, mainly driven by biomass, large-scale heat pumps and excess heat from industrial processes. Moreover, parallel to the penetration of intermittent renewable sources in the power sector, a transition to the low-temperature 4th generation DH systems in the period from 2020 to 2050 has been anticipated [15]. Li & Svendsen developed a model of hypothetical low temperature DH network in Denmark and their analysis concluded that such systems are characterized by significantly lower heat losses than traditional systems, as well as by reduced exergy losses [16]. All of the above proves the importance of the DH in Denmark. Improving any part of the DH system

can lead to large savings in the total system costs on a country level. Furthermore, internalizing the external costs can show further benefits of the DH systems. Zvingilaite showed for the case of the Danish heat and power sector that the inclusion of human health-related externalities in energy system modelling can lead to results with an 18% decrease in the total health costs and a 4% decrease in the total energy system costs, compared to models where such externalities are excluded [17].

Some authors have focused on the integration of geographically distributed DHs, on the possibility of establishing pricing mechanisms similar to day-ahead electricity markets and on addressing the problem of the monopolistic position of DH suppliers when they also operate the DH grid. Gebremedhin & Moshfegh first modelled a locally deregulated integrated district heating system [18]. They developed the MODEST tool for analyses and assessed the potential of connecting 7 geographically dispersed DH systems. However, their conclusions were vague and uncertain. Further development of their model was carried out by Karlsson et al. [19]. They concluded that the economic potential for a heat market in three different Swedish DH systems amounts to between 5 and 26 million €/year with payback times ranging from two to eleven years. Moreover, they showed that connecting different DH grids can reduce the total CO₂ emissions. However, their economic indicator is a bit unclear, as it is a mix of a business-economic and a socio-economic one. Syri & Wirgentius developed a model which simulates a day ahead heat market, in the same fashion as the well-known day-ahead electricity spot market operates today [20]. They adopted the model for the city of Espoo in Finland and concluded that an open heat market can be beneficial for all parties involved and significant fuel savings could be achieved. Kimming et al. recently showed the beneficial outcome of vertically integrated local fuel producers into district heating systems [21]. Their proposed integration can lead to the reduction of greenhouse gas (GHG) emissions and lower the production costs/heat price, if there is an incentive to utilize locally produced fuels.

In order to assess both the economic and technical benefits that can be obtained by interconnecting adjacent district heating systems, a model was developed that represents different DH systems with their geographical bounds, together with the power and gas sectors. Moreover, it is an hourly model which can easily cope with modelling of large amounts of intermittent power sources. The model allows users to assess the feasibility of interconnecting different DH systems from a technical and socio-economic point of view, as well as to analyse the possible changes in the scheduling of each heat supplying plant that may occur after the interconnection of systems has been implemented. The novelty of this model compared to the previously developed ones is the representation of the whole energy system together with the representation of physical boundaries of DH systems on an hourly basis, which does not cause problems in modelling the large amounts of intermittent sources. Moreover, it can optimize utilization rates of different energy plants, as well as investments in new ones. The model developed and the results presented could be used for further understanding of impacts of DH systems on the flexibility of the power sector.

As opposed to the electricity grid whose size of the transmission grid allows many different suppliers to connect and interact with different types of demand, DH grids are geographically constrained to usually only densely populated regions. Sometimes heat suppliers are also the owners of the DH grid which then constitutes a complete monopoly. Another solution is when heat suppliers and the DH grid are operated by at least two different independent bodies. The competition among suppliers can lead to the increased operational efficiency and consequently costs of energy production can be reduced, when equal access to the distribution network is

secured to all suppliers [22]. However, even if the latter condition is satisfied, in smaller cities it is often the case that there is only one company supplying all the heat. This can lead to inefficiencies in the system as the lack of competition among the suppliers might drive them away of the reduction of the production costs. The authors of this paper developed a model which can assess the technical and economic benefits of connecting adjacent DH grids and allowing a larger integration between the power and heating sectors. Furthermore, the model developed allows optimizing investments in the energy sector taking into account current investments as sunk costs, i.e. costs that occurred and cannot be recovered anymore. This can allow planners to assess whether an existing DH system can be improved and become cheaper in terms of socio-economic costs.

Thus, the aim of the model is to be used for assessing whether the integration of adjacent district heating grids can lead to the fuel savings (if more energy efficient heat producers can supply their energy to a larger number of customers) or reduced CO₂ emissions (if lower emission emitters are deployed more often after they get the chance to supply more customers), in the same time not threatening to economic competitiveness of the energy system. In case of positive results of the chosen case studies, it would be an important contribution towards meeting the European as well the as Danish national climate policy goals.

Following the description of the developed model in the subsequent chapter, a case study chosen in this paper is described in chapter 3. Results of the case studies, showing the outcome of the considered interconnections between different DH systems for both the current and the future energy system, are presented in chapter 4, followed by the discussion of the results, including a comparison with other work in the field, and finishing with the most important conclusions of this paper.

2. Methods

2.1. Model description

The model developed is a linear continuous programming model which makes it possible to run it on personal computers, although there is a vast amount of variables used. Although models such as TIMES and MARKAL use decomposition techniques and typical days to represent one year, it is argued that this representation cannot account for weather variations properly [23]. Also, it cannot represent a consistent criterion to select days or weeks or to assess the validity of assumptions [24]. Furthermore, problems concerning the representation of flexible energy technologies and storage plants have been detected [25]. In order to cope with these issues, the authors of this paper have decided to represent the energy system during the one year using an hourly temporal resolution. Although building an optimization model with numerous technologies and with an hourly time-resolution can lead to significant computational challenges, it is beneficial that all the possible relations between the weather data (wind speeds and solar insolation), prices of the commodities on the markets (day ahead el-spot market), seasonal, monthly, weekly and daily demand variations as well as storage technology dynamics can be taken into account. The model seeks to find the least cost solution of the energy system. Its outputs are the hourly generation of different technologies, heat storage levels in every hour during the year and capacities of the energy plants. Furthermore, the model calculates post-optimization total primary energy supply (PES) and CO₂ emissions.

Socio-economic costs were used to represent the costs of the energy system. Socio-economic costs are a good way to represent the *true* costs imposed on society from operating an energy system

as it takes a broad perspective into account when reporting the costs. Generally, socio-economic costs do not take taxes and subsidies into account (as opposed to business-economic costs) as they are considered to be internally redistributed within the society. Detailed discussion on the difference between socio-economic and business-economic costs when analysing energy systems can be found in Ref. [26]. In our approach, investment costs, fixed and variable operating and maintenance (O&M) costs, fuel costs and CO₂ emissions price were taken into account when calculating the total socio-economic cost of the energy system. Although the concept can be expanded by including other negative health externalities such as NO_x, CO and SO₂ emissions, as well as the potential for job creation, it was left outside of the scope of this paper as it is less clear how these costs should be internalized.

2.2. Mathematical description

The developed linear continuous model consists of an objective function, inequality constraints, equality constraints as well as upper and lower bounds. In order to make it easier to follow the equations, abbreviations of the equation terms can be seen in the Nomenclature chapter.

2.2.1. Objective function and variables

The objective function in this model is set to minimize the total annual socio-economic costs:

$$\begin{aligned} \min Z = & \sum_{i=1}^n (\text{fix_O\&M}_i + \text{lev}_{\text{inv}_i}) x_i + \sum_{j=1}^m \left(\text{var_O\&M}_j + \frac{\text{fuel}_j}{\eta_j} \right. \\ & \left. + \text{CO}_{2j} \cdot \text{CO}_{2\text{inten}_j} \right) x_j + \sum_{k=1}^p (\text{el_imp_exp}_k \\ & + \text{gas_imp_exp}_k + \text{dies_imp}_k + \text{petr_imp}_k) x_k \end{aligned} \quad (1)$$

The first term in (1) represents the fixed O&M costs and leveled investments in generation capacity over the lifetime of an energy plant. The second term calculates the variable, fuel and CO₂ emission costs while the last term calculates expenditures for electricity, gas, diesel and petrol import or electricity and gas export. As no generation of fuels usually exists in smaller regions (at a municipal level), diesel and gasoline cannot be exported outside of the system's boundaries in this model. However, if needed, this constraint can be easily removed. Note that the x_i set of variables are capacity variables and thus, their unit is MW, while x_j and x_k are generation, import or export amounts in an hour. Hence, their unit is MWh.

Levelized investments are calculated using (2):

$$\text{lev}_{\text{inv}_i} = \text{inv}_i \cdot \frac{\text{dis_rate}_i}{1 - (1 + \text{dis_rate}_i)^{-\text{lifetime}_i}} \quad (2)$$

In order to make it easier to follow the inequality and equality constraints, the variables x_i , x_j and x_k are further associated with indices in order to make it clear what type of their output is and what type of fuel they use. A description of the indices can be found in Table 1. Generally, the first index describes the ordinal number of technology, the second index describes the type of the output from a certain technology and the third index describes the fuel type that the technology is using. In the case of heat generation and storage technologies, a fourth index specifies in which of the geographically separated DH systems the technology operates.

2.2.2. Inequality and equality constraints

Inequality constraints represent the heating demand to be met

Table 1
Explanation of variables.

Variable	Subdivision	Subdivision 2	Explanation
x_j	$x_{j,EL}$	$x_{j,EL,gas}$	Hourly generation of technologies which generate electricity and are driven by gas
		$x_{j,EL,biomass}$	Hourly generation of technologies which generate electricity and are driven by biomass
		$x_{j,EL,other}$	Hourly generation of technologies which generate electricity and are driven by other fuel types
	$x_{j,heat}$	$x_{j,heat,gas}$	$x_{j,heat,gas,t}$ Hourly generation of technologies which generate heat, are driven by gas and operate in the DH system t (t represents the number of geographically separated DH systems; number of DH grids = 1, 2... t)
		$x_{j,heat,biomass}$	$x_{j,heat,biomass,t}$ Hourly generation of technologies which generate heat, are driven by biomass and operate in the DH system t
		$x_{j,heat,other}$	$x_{j,heat,other,t}$ Hourly generation of technologies which generate heat, are driven by other fuel types and operate in the DH system t
		$x_{j,heat,storage_ch}$	$x_{j,heat,storage_ch,t}$ Hourly charge of heat to the heat storage operated in the DH system t
		$x_{j,heat,storage_dis}$	$x_{j,heat,storage_dis,t}$ Hourly discharge of heat from the heat storage operated in the DH system t
	x_{j,an_dig}		Generation of gas after CO ₂ removal in anaerobic digester (an_dig denotes anaerobic digestion)

in each DH grid, as well as the electricity, gas, diesel and gasoline demand to be met by the generation technologies or from import in each hour during the year. The number of hours in one year was set to 8760. Mathematically, this can be represented in the following way (note that due to the simplification of representation, the *sum* sign has been dropped out in the following notation):

The set of constraints for meeting the heat demand in each DH grid are modelled in (3):

$$x_{j,heat,gas,t} + x_{j,heat,biomass,t} + x_{j,heat,other,t} + x_{j,heat,storage_dis,t} - x_{j,heat,storage_ch,t} \geq heat_dem_t \quad (3)$$

In order to model a connection of two or more DH grids, the constraint presented in (4) needs to be adopted:

$$\begin{aligned} & x_{j,heat,gas,1} + x_{j,heat,biomass,1} + x_{j,heat,other,1} + x_{j,heat,storage_dis,1} \\ & - x_{j,heat,storage_ch,1} + x_{j,heat,gas,2} + x_{j,heat,biomass,2} \\ & + x_{j,heat,other,2} + x_{j,heat,storage_dis,2} - x_{j,heat,storage_ch,2} \\ & + \dots + x_{j,heat,gas,t} + x_{j,heat,biomass,t} + x_{j,heat,other,t} \\ & + x_{j,heat,storage_dis,t} - x_{j,heat,storage_ch,t} \geq heat_dem_1 \\ & + heat_dem_2 + \dots + heat_dem_t \end{aligned} \quad (4)$$

The index t in the upper constraint represents the number of DH grids one wants to connect.

Furthermore, the set of constraints for meeting the electricity demand is defined in (5):

$$x_{j,EL,gas} + x_{j,EL,biomass} + x_{j,EL,other} + el_imp_exp_k \geq el_dem \quad (5)$$

Equation (6) shows the set of constraints for meeting the gas demand:

$$x_{j,an_dig} + gas_imp_exp_k - \frac{x_{j,heat,gas,t}}{\eta_j} - \frac{x_{j,EL,gas}}{\eta_j} \geq gas_dem \quad (6)$$

The set of constraints for meeting the gasoline and diesel demand is given in (7) and (8):

$$dies_imp_k \geq dies_dem \quad (7)$$

$$petr_imp_k \geq petr_dem \quad (8)$$

In (9), the set of constraints for assuring that the capacity of energy plants is large enough for the peak production of the specific technology is shown:

$$x_j \leq x_i \cdot t \quad (9)$$

where t denotes the time of 1 h. Thus, $x_i \cdot t$ has the unit of MWh.

Moreover, it needs to be assured that the capacity of the transmission grid, gas grid and fuel grid is large enough for importing/exporting different types of energy in each hour, which is defined in (10):

$$x_k \leq x_i \cdot t \quad (10)$$

Equations (9) and (10) are valid for every hour throughout the year. Finally, there are constraints for biomass consumption and maximum CO₂ emissions that can be optionally imposed in the model, presented in (11) and (12):

$$CO2_{inten_j} \cdot x_j + CO2_{inten_k} \cdot x_k \leq CO2_{cap} \quad (11)$$

$$\frac{x_{j,EL,biomass}}{\eta_{j,EL}} + \frac{x_{j,heat,biomass}}{\eta_{j,heat}} \leq bio_cap \quad (12)$$

The second term in constraint (11) denotes that the emissions of the energy coming in or out of the system boundaries are also taken into account.

Heat storage can be modelled in several ways. However, in order to avoid the implementation of for-loops, which increases the computational time significantly, this model uses an equality constraint set for each hour r :

$$heat_level_r = heat_level_{r-1} + x_{j,heat,storage_ch,r} - x_{j,heat,storage_dis,r} \quad (13)$$

Furthermore, in the first and the last hour of the year, storage level is set to zero:

$$heat_level_1 = heat_level_{8760} = 0 \quad (14)$$

Finally, the discharged energy from the storage needs to be lower or equal to the storage content in the hour before:

$$heat_level_{r-1} \geq x_{j,heat,storage_dis,r} \quad (15)$$

2.2.3. Upper and lower bounds

The decision of upper and lower bounds can be set by the modeller for each specific case. However, it should be noted that variables denoting import and export of the electricity and gas are unconstrained in sign, as they are positive for import of energy and negative for export of energy across the system boundaries:

$$el_imp_exp_k, gas_imp_exp_k \dots \text{unconstrained in sign}$$

In this model, export of diesel and petrol fuels has not been considered.

All other variables need to be positive in sign. However, the infrastructure, including energy plants, being already built shall be modelled as sunk costs, i.e. costs that have already occurred and cannot be recovered anymore. Thus, eventual new investments need to be feasible enough to compensate for the sunk costs in order to reduce the total socio-economic cost of the energy system. Sunk costs of the energy plants already being built are modelled by setting the lower bounds of capacity variables of these energy plants to the output capacities of the plants. In that way, the model takes these investments into account when minimizing the total socio-economic cost of the system, while the capacity of already built energy plants will be available for energy generation.

It should be noted that any energy storage, such as gas, biogas or fuel storages, can be modelled in the same manner using (13) and (14).

2.2.4. Exogenous variables

Individual demand for heating, as well as industry demand for fuel types not considered here (such as coal) shall be entered into the model exogenously. In that way, the emissions and the cost of these types of energy can be accounted for in the model.

2.3. Indicators

One can distinguish between the economic and technical indicators used in the model. Economic indicators are represented by the total annual socio-economic cost, while the indicator of the technical feasibility of the system is the CO₂ emission level. However, it should be noted that the objective value of the model is to minimize the total socio-economic costs, while the CO₂ emission level can (but does not need to) be constrained using the CO₂ emission capacity. In any case, CO₂ emissions are calculated post-optimization.

Furthermore, in order to calculate the feasibility of interconnections between different DH grids, several economic indicators were used. In this paper, economic evaluation was conducted using the net present value (NPV) method. NPV sums up all payments related to the investment (both positive and negative) over a certain period of time, incorporating the discount rate to the temporal distribution of the payments.

Investment in piping needed for connecting two DH grids is considered as a cost occurring in the beginning of the project, while the difference between total socio-economic costs before and after connecting the DH grids is considered as saving, occurring at the end of each year during the project lifetime. The investment and the savings are the input payments (the investment as a negative payment and savings as a positive payment) for the calculation of NPV values.

In order to make it easier to assess the results, as well as to increase their clarity, the dynamic payback time and internal rate of return (IRR) values were calculated. The dynamic payback time determines how long it takes for the net present value of the annual payments to cover the investment, while IRR represents the discount rate at which the net present value is equal to zero.

Generally, a project is considered to be profitable if NPV is higher than zero, the dynamic payback time is lower than the defined project lifetime and the IRR is higher than the discount rate.

2.4. Investment calculation in the interconnecting piping

In order to carry out a feasibility analysis of different cases, the price of the interconnecting pipes had to be assessed. As the transmission piping is the sole investment compared to the official

plans for the energy transition of the region, its careful and accurate estimation is of crucial importance. As the price highly depends on the pipe diameter, it was necessary to determine the nominal diameter (DN) of each of the interconnecting pipes. A comprehensive description of district heating and cooling systems, from the fundamental idea to the detailed elaboration of system functioning, economics and planning has been provided by Frederiksen & Werner in their book “District Heating and Cooling” [27]. Among other methods, theories, examples and descriptions, they offer two very useful relations. The first is the relation between velocity of the flow in district heating pipes and the pipe diameter, whereas the second is the relation between the pipe diameter and the investment price of district grid expansion expressed per meter of the piping length, based on investments in Swedish district heating networks. As the maturity of Swedish DH system, as well as its market share, is pretty similar to those of Danish DH systems, it is considered that the same relations are applicable for the case of a DH system located in Denmark. The pipe diameter was determined using the relation between the velocity of the flow and the pipe diameter, according to the following set of equations:

$$\dot{m}_{max} = \frac{\varphi_{max}}{c_w * \Delta T} \quad (16)$$

Where:

\dot{m}_{max} - maximum mass flow of the water transferred through the pipes, kg/s

φ_{max} - maximum heat capacity transferred through the pipes, W

c_w - specific heat capacity of water, 4.187 kJ/(kg × K)

ΔT - water temperature difference, K

$$q_{v, max} = \frac{\dot{m}_{max}}{\rho_w} \quad (17)$$

Where:

$q_{v, max}$ - maximum volume flow of the water transferred through the pipes, kg/s

ρ_w - water density, 1000 kg/m³

$$A_p = \frac{q_{v, max}}{v_f} \quad (18)$$

Where:

A_p - cross area of the pipe, m²

v_f - flow velocity, m/s

$$DN = 2 * \sqrt{\frac{A_p}{\pi}} * 1000 \quad (19)$$

Where DN is nominal diameter of the pipe in millimetres.

Knowing the maximum hourly heat capacity transferred through each pipe, which is one of the outputs of the developed mathematical model, and using (16) and (17), it was possible to calculate the maximum hourly volume flow of the water going through the pipes. The flow velocity was determined using (18) and (19) and an iterative method of matching the flow speed and the diameter of new transmission piping. The final result was the pipe nominal diameter for each of the cases.

Furthermore, knowing the nominal diameter of each pipe and using the relation between the pipe diameter and the investment price of piping per meter of the length reported in Ref. [27], it was possible to estimate the piping price. It is important to emphasize that the reported relation distinguishes between four different areas where an investment can be made: inner city areas, outer city areas, park areas and construction site areas. In this case, the transmission pipes are connecting DH systems between towns,

which can be considered as outer city areas. Hence, reported values for outer city areas were used in this paper. Detailed results of the piping price estimation steps are given in section 4.2.

3. Case study

The Danish municipality of Sønderborg was chosen as a case study in this work. It is a medium-sized municipality in a Danish context with approximately 75,000 inhabitants and an area of around 496 km². The largest town in the municipality is Sønderborg town with a population of about 27,500; other towns in the municipality have a population of less than 7000. The municipality has the goal of becoming CO₂ neutral by the year 2029. This goal and the municipality's efforts to reach the goal, such as the operation of the ProjectZero office [28], make Sønderborg an interesting case study and furthermore leads to good availability of data and future projections about its energy system.

Table 2 shows the final energy consumption in the municipality in 2013 by type. The total final energy consumption was 2.15 TWh, leading to the emission of 500 kilotons* of CO₂.

As in the most municipalities in Denmark, DH plays a large role in the heating sector of Sønderborg's energy system. There are currently five separate DH systems in operation in the municipality, Sønderborg town DH being the largest by far. The gross consumption in each DH system is shown in Table 3.

Sønderborg municipality is currently a net importer of electricity. The total electricity consumption in the municipality in 2013 (including electricity for heating, process and transport) was 502 GWh. Electricity generation within the municipal borders was 91 GWh in the same year, corresponding to 18% of the total consumption. There is currently no gas or biogas production in the municipality. All natural gas consumed in the municipality is therefore imported from the national gas distribution grid.

As mentioned in the methodology chapter, the investment costs of the already existing energy plants were modelled as sunk costs. Thus, the capacity variables presented in Table 4 (including the ones from Fig. 1) were set as lower bounds for the system in the reference year.

Although the majority of the electrical energy was imported in the reference year, it is interesting that 67% of the municipal electricity production came from renewable sources (according to the Danish Energy Agency 55% of waste incineration produced electricity can be regarded as renewable [31]). However, 80% of the total municipal electricity demand was met by importing electricity [29].

3.1. Case studies in the reference year

After setting up the model for the Sønderborg case, the model was validated by comparing the results with the figures presented above. The outcome of the model for the reference year will be designated as a case I. Case II represents the Sønderborg system after the DH system of Sønderborg (town) and Augustenborg have been connected. In case III, Broager DH will be connected with Sønderborg and Augustenborg DH grids. In case IV, Gråsten DH is connected and finally, in case V Nordborg DH is connected with other DH grids. Thus, in case V all the DH systems are interconnected, as opposite to case I, in which none of the DH systems are interconnected. For the sake of clarity, the interconnections between different DH systems are presented in Table 5, too. Please refer to Fig. 1 in order to make it easier to understand the ordering of DH systems being interconnected.

The model assumes that as soon as one interconnection has been made, the investment in it represents a sunk cost as the system cannot be returned to the starting point. Thus, after the interconnection between Sønderborg and Augustenborg has been set (case II), the two merged different DH systems present a new system that is a starting point for the following mergers. Hence, savings after merging the Broager in case III are the difference in total socio-economic costs between case II and case III, and not between the starting case (case I) and case III. Furthermore, investment in piping for merging Broager (case III) is only calculated as a piping construction between Broager and Sønderborg, as it is assumed that the piping between Sønderborg and Augustenborg has been built already. The same principle goes for cases IV and V.

Hourly electricity and gas consumption profiles were obtained from the Danish electricity and gas transmission system operator

Table 2

The total final energy consumption and CO₂ emissions in Sønderborg municipality in the year 2013 [29].

	Final energy consumption (GWh/year)	CO ₂ emissions (kton/year)
District heating	488	42
Individual heating	438	104
Electricity (classical) ^b	442	158
Process energy	270	64
Transport	510	133
Total	2148	500^a

^a In the report used as a reference for the base year, CO₂ emissions from waste incineration plant were calculated as zero. However, using the recommendation from Danish energy agency, a part of the CO₂ emissions from waste incineration plant has to be taken into account. This would account for additional 28.57 kilotons of CO₂ emissions during the year.

^b Electricity consumption for district heating, individual heating, process energy and transport is not included in the value for classical electricity consumption in the table. Electricity demand for powering cooling devices is included in the value.

Table 3

Heat generation capacity in 2013 and the gross district heating production in Sønderborg municipality's five district heating networks [29].

DH production by network ^a	Installed capacity (MW)	Production (GWh/year)	Storage capacity ^b [m ³]
Sønderborg	201.5	349.0	4000 (232.4 MWh)
Gråsten	46.7	41.6	8500 (493.9 MWh)
Augustenborg	28.6	35.3	—
Nordborg	24.1	33.3	—
Broager	24.9	28.3	4500 (261.5 MWh)
Total	325.8	487.6	

^a The heating year 2013 refers to the period from July 2013 until June 2014. The data has been corrected for degree days.

^b Storage size of the tank coupled with the solar district heating plant in Sønderborg was obtained from Ref. [30]. Storage size for other two storages were scaled depending on the capacities of the solar district heating plants.

Table 4

The installed capacities and the electricity generation in Sønderborg municipality in 2013 by power plant type [29].

Electricity production	Installed capacity 2013 (MW)	Production 2013 (GWh)
Waste incineration CHP	4.5	36
Natural gas CHP	71.4	14
Wind turbines	14.6	29
Photovoltaics	14.8	12
Total	103.8	91

(TSO) for the modelled region. As a part of the ongoing CITIES project [32], an hourly measured data from 53 district heating customers were obtained for Sønderborg. As the yearly district heating consumptions were provided by the respective district heating providers, an hourly pattern was estimated by scaling the available hourly data to the yearly consumption values.

3.2. Case studies for the year 2029

As previously mentioned, the municipality of Sønderborg intends to become CO₂ neutral by 2029. A roadmap for achieving this has been reported in Ref. [33]. However, the final steps in the transition have not been planned yet, as the CO₂ emissions upon implementing all currently planned measures are reported to be 130 ktos (not including the 28.57 ktos of CO₂ emissions from the waste incineration plant), mainly from the transportation sector. Furthermore, in the mentioned report, due to the constraints of the

model being used (EnergyPLAN [34]), DH systems were considered as interconnected. However, it was not specified at all how this interconnection should be achieved or what the costs of achieving this transition would be.

In order to assess the potential consequences of interconnections between different DH systems in 2029, case VI was modelled as a reference case that can be compared with the official plans, having all the DH systems separated, as it is the situation today. On the other hand, case VII was modelled with the energy plants capacities stated in the official plan, however this time with all the DH systems interconnected. Capacities that are changed in comparison with the reference year are shown in Table 6.

Case studies modelled in this way also allow a comparison between the socio-economic benefits of connecting DH systems when electricity and gas imports are dominating the system, as it is the case in the reference year, and when electricity and gas exports are dominating the system, as according to Sønderborg municipality's

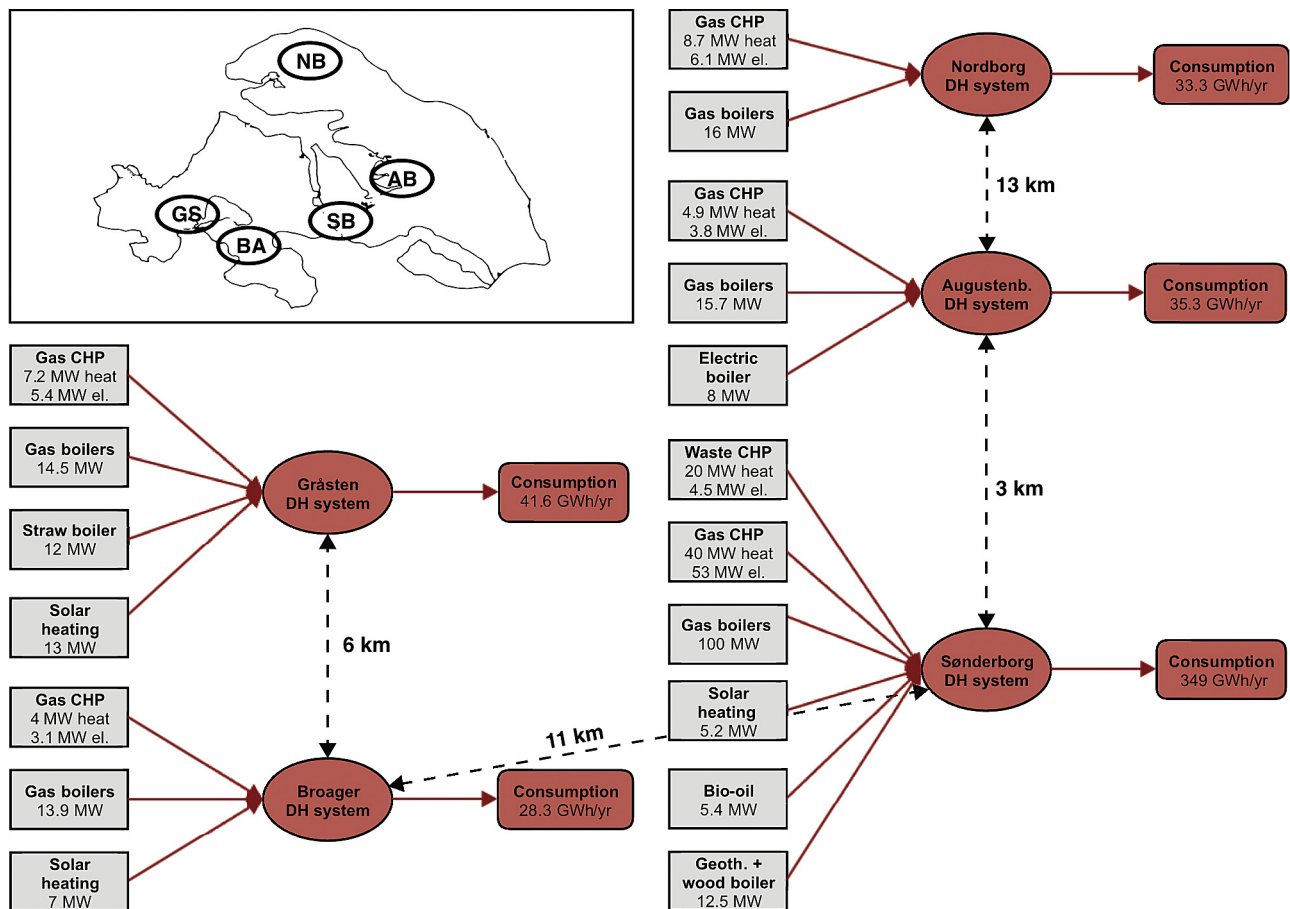


Fig. 1. A schematic representation of Sønderborg municipality's five DH systems. For each DH system, the power plant types and installed capacities are shown on the left and the total annual gross heat consumption (2013 values) is shown on the right. Possible future interconnections between the DH systems are shown with dashed lines, along with the approximate straight-line distance between adjacent DH systems. Inset: The geographical outlines of Sønderborg municipality, with the locations of the five district heating systems shown in circles.

Table 5
Description of interconnections in different cases.

Case	Interconnected DH systems
I	5 separated DHs
II	Merged Sønderborg (town) and Augustenborg
III	Merged Broager, Sønderborg and Augustenborg
IV	Merged Gråsten, Broager, Sønderborg and Augustenborg
V	Merged all five DH

roadmap for the year 2029.

The demand for electricity, gas and district heating was adopted from the ProjectZero's official plan for transition towards the carbon neutral Sønderborg in the year 2029 [36]. An important aspect of the plan is that the demand for district heating is expected to rise from 487.6 GWh to 535.7 GWh, although significant energy efficiency measures are expected to be adopted. The reason for the latter is the active policy towards connecting buildings to the DH grid whenever socio-economic costs prove to be favourable towards it. More specifically, the project report [36] states that an additional 18% of the heating demand will be converted to DH, while the total energy savings for heating will amount to 35% compared to the 2007 consumption levels.

The coefficient of performance (COP) for the large scale heat pumps, used in the calculations for the year 2029, was assumed to be fixed at 3.0. A proper and detailed discussion whether this assumption is valid was carried out in Ref. [37]. The authors concluded that there was not much difference between the scenarios with and without the assumption of a fixed COP, as it changes only by a few percent on a weekly basis due to the inertia of the temperature of the heat source.

3.3. Waste heat potential in the year 2029

An additional two cases were developed in order to assess the potential impact of waste heat from the nearby industry on the future district heating grid. This was done both for the geographically distributed and interconnected cases. One should recall here

that the case VI presents the anticipated DH system in the year 2029 where no interconnections are made, while case VII presents the fully interconnected DH system of the year 2029.

Case VIII presents the same energy supply mix as case VI, except that the additional waste heat from industry was assumed to be available for supply to the geographically distributed DH systems. Case IX presents the same industrial waste heat supply potential as in case VIII, but in the fully interconnected DH grid.

The investment cost in the waste heat recuperators and connection piping to the DH grid were taken into account as a single investment, levelized during the equipment lifetime and reported as a part of the total system costs. Investment and fixed operating and maintenance costs are as reported in Table 9, while variable operating and maintenance and fuel costs were set to zero, as this heat would otherwise be wasted.

A screening of the industry located within the municipality revealed that the tile works factories had the largest potentials, as well as the most suitable supply temperatures, for delivering waste heat to the DH grid. Appropriate allocation of waste heat resources could be elaborated more as part of further work using Pinch Analysis [38]. An example of recovering waste heat in the cement production for the case of a cement factory in Croatia, using the principals of Pinch Analysis, was presented in Ref. [39].

In the present case, there were in total five tile work factories that were operating in 2013; two near the Gråsten DH grid and three near the Broager DH grid.

Out of the total consumed energy, an estimated share of the energy that could be fed into the DH grid as a waste heat was taken from Ref. [40]. The data for the cement industry was used for the tile works factories as it was found that the temperature levels of the waste heat of cement and tile works industries are fairly similar [41]. Detailed estimation of the industrial waste heat potential can be seen in Table 7.

The table leads to the conclusion that in case VIII, the two factories located near the Gråsten DH system can deliver the waste heat only to the Gråsten DH system, while the three factories located in the vicinity of Broager DH system can deliver their heat only to the Broager DH system. On the other hand, in case IX,

Table 6
Capacities of energy plants according to the official plans [33].

	Installed capacity 2013 (MW)	Installed capacity 2029 (MW)
Anaerobic digestion	0	42
Gas boilers	105	55
Geothermal heat coupled with absorption heat pump ^a	0 ^b	12.5
Biomass boilers	19	28
Large scale heat pumps	0	50 (heating capacity)
Solar heating	24	24
Heat storage	988 MWh	2300 MWh
Wind turbines	14.6	180
Photovoltaics	14.8	60

^a Geothermal heat at 44 °C is boosted to 82 °C via a biomass driven absorption heat pump [35]. If the geothermal heat is considered as “free” heat, this combination can be modelled as a biomass boiler with $\eta = 135\%$.

^b This unit started to be tested in the year 2013; hence, its generation started to be calculated only from the year 2014 and therefore it is not present in the reference year (2013).

Table 7
Industrial waste heat potential estimation of the suitable factories located in the municipality.

Plant	Heating oil [GWh]	Ngas [GWh]	Coal/coke [GWh]	Electricity [GWh]	Waste heat [GWh]	Closest DH	Distance to closest DH [km]	Ref
Gråsten Teglværk	0.75	38.50	0	4.50	9.60	Gråsten	0.20	[42]
Petersen Tegl Egersund	0.34	3.30	18.47	2.15	5.43	Broager	2.35	[43]
Carl Matzens Teglværker	0.30	13.75	0	1.22	3.35	Gråsten	2.42	[44]
Bachmanns Teglværk	0.35	0.00	0	10.00	2.21	Broager	3.21	[45]
Vesterled Teglværk	0.40	55.00	0	5.50	13.29	Broager	4.10	[46]
Total	1.78	110.55	18.47	23.37	33.89			

industrial waste heat from all the five factories is delivered to the fully interconnected DH grid.

3.4. Modelling the case study

This specific case study, using the methodology described in this paper, consists of the following matrix sizes in the model:

Taking into account that Matlab uses 8 bytes of memory for storing one number of type *double*, the problem stated above would present a significant amount of random access memory (RAM) to be loaded. Specifically, if all the numbers would be of type *double*, the problem stated in Table 8 would require almost 3.5 terabytes (TB) of RAM memory. However, by exploiting the fact that the most of the numbers inside the matrices are equal to zero, using the sparse function, the memory need can be significantly reduced. In this specific case, the memory needed for constructing the optimization problem is equal to 57 megabytes (MB). For fully loading all the variables and the optimization model, the RAM requirements rise to approximately 80 MB. However, this shows that the implementation of models with a complexity on this level requires the utilization of the sparsity of matrices.

Several cost assumptions have been used to obtain the results. Technology costs occurring in the case study are shown in Table 9.

The CO₂ intensities were obtained from the Danish Energy Agency [53], while the discount rate was set to 4%, which is the rate recommended by the Danish Ministry of Finance for socioeconomic analyses [54]. CO₂ emissions of imported electricity were set to the average emissions of all the electricity generation in Denmark, equalled to 0.478 tCO₂/MWh. Carbon dioxide intensity of the electricity generation is expected to fall down until 2029. In Ref. [55], the Danish TSO calculated expected CO₂ intensity of the electricity generation to be 0.3 tCO₂/MWh in the year 2024. Using linear extrapolation and the latter two values, estimated CO₂ intensity of the electricity production for the year 2029 was 0.22 tCO₂/MWh.

Table 8
Matrix sizes of the optimization problem.

	Size of the matrix
Objective function	595,750 × 1
Inequality constraints	674,520 × 595,750
Equality constraints	52,560 × 595,750
Upper bounds	595,750 × 1
Lower bounds	595,750 × 1

Table 9
Technology cost sheet used for the case study. ^a

	Investment cost [€/MW]	Fixed O&M [€/MW]	Variable O&M [€/MWh]	Fuel cost [€/MWh]	Lifetime	Ref
Solar thermal heating	562,000	1500	1.00	0	30	[47]
Geothermal heating with absorption heat pump	1,600,000	37,000	0	0	25	[48]
Large scale heat pump	680,000	5500	12.93	^b	20	[48]
Biomass boiler	800,000	0	5.40	^c	20	[48]
Gas boiler	100,000	3700	5.40	^c	35	[48]
Electric boiler	75,000	1100	13.43	0	20	[48]
Waste CHP	8,500,000	16,500	23.00	0	20	[48]
Gas CHP	1,050,000	250,000	3.90	44.00 [49]	20	[50]
Wind turbine (onshore)	1,200,000	36,000	1.00	0	20	[48]
PV	1,000,000	30,000	1.00	0	30	[48]
Waste heat recuperators and piping connection to DH	160,000	4000	0	0	20	[51]
Anaerobic digestion	10,000,000	54,000	5.60	0	20	[52]
Seasonal heat storage [€/m ³]	35	0.01	—	0	20	[48]

^a Storage costs are not included in costs of specific technologies (e.g. boilers or CHPs), but they are given separately at the bottom of the table.

^b The cost of the electricity on the Nordpool day ahead market increased for transmission and distribution tariff (changes hourly).

^c Please refer to Table 10.

Increased losses in the DH grid, after the interconnections are implemented, are another consideration that needs to be taken into account. As reported in Ref. [56] for the DH system in Iceland, using well-insulated piping for the main distribution line with the length of 18 km led to a temperature drop of 1.5 °C along the way. As the model developed here is not a dynamic one with the feedback loops included, losses of the DH grid needed to be assumed. In order to estimate the losses and still be on the safe side, the situation in which all the heat to the newly connected DH grids would come from central DH system in Sønderborg (town) as the worst case has been chosen. By taking into account the supply and return temperatures of 75/50 °C, additional heat losses of 1.5% of the total gross DH supply were added on top of the total DH heat demand.

Optimization was run using the Gurobi® 6.5.0 solver using the Matlab® R2015b interface to build the model. The personal computer (PC) used to run the model has Intel® Core i7 CPU processor working at frequency of 2.60 GHz, 8 GBs of RAM memory and 220 GBs of storage on an SSD hard-disc. The operating system was 64-bit Windows 7 Enterprise. On the described PC, one run of the optimization model takes between 30 and 120 s.

3.5. Fuel, electricity and CO₂ prices

Assumptions made by the Danish TSO, Energinet.dk, were used to determine prices of fuels used in the system both in 2013 and 2029. The prices are shown in Table 10. Their assumptions are based on the International Energy Agency's (IEA) data, except for the biomass price, which follows assumptions made by the Danish Energy Agency (DEA) [57]. An increase in the fuel prices in the period 2013–2029 is expected for all the fuels, on average being 16.08%. The price of fuel oil is expected to increase the most in this period, or by 22.44%, whereas natural gas price is expected to show the least increase, or for 10.12%.

An hourly distribution of electricity prices in 2013 was obtained from Ref. [58], where the data for day-ahead spot market in Western Denmark (DK-West) was used, as Sønderborg

Table 10
Fuel prices used in the model for the system in the year 2013 and 2029 [57].

	2013	2029
Coal [€/MWh]	10.47	12.58
Natural gas [€/MWh]	32.71	36.02
Fuel oil [€/MWh]	46.11	56.46
Biomass [€/MWh]	28.81	32.17
Average electricity price [€/MWh]	38.98	61.34

Table 11
A comparison of the model's output and the official data.

Total energy consumption	Consumption – official data (GWh/yr) [29,33]	Model reference case (case I) (GWh/yr)	Difference [%]	CO ₂ emissions (including waste) – official data (kton/yr)	Model reference case (case I) (kton/yr)
Gas	571.9	571.3	–0.11%	528.57	521.88
Coal	13.6	13.6	0.00%		
Heating oil	116.0	116	0.00%		
Wood and straw	188.1	213.1	13.31%		
Individual heat pumps	21.2	21.2	0.00%		
Individual electric heating	53.5	53.5	–0.01%		
Waste consumption	212.5	215.4	1.36%		
Classical electricity	442	440.5	–0.34%		
Diesel and gasoline	506.8	506.3	–0.09%		
Other and unknown	22.4	0	–100.00%		
Total	2148	2151	0.14%		

municipality is located in that region. For the future system in 2029, assumptions regarding the average electricity price growth made by Energinet.dk were used to modify the hourly distribution throughout the year. All fuel and electricity prices are presented in Table 10.

As already mentioned when describing how the socio-economic costs were calculated in the methods section, internalized climate change externality in terms of costs of CO₂ emission allowances were taken into account in a form of average emissions price. CO₂ emission price was set to 4.5 €/t in 2013 [59] and 25.37 €/t in 2029 [57].

4. Results

4.1. Validating the model

In order to validate the model, a comparison of its results with the official data on primary energy consumption in Sønderborg municipality has been made. The result can be seen in Table 11.

Comparing the output of the reference case in the model with the data obtained from the official publications, a similar consumption per fuel types has been obtained. With the exception of biomass and waste consumption, all the other fuels differ by less than 1%. A slightly higher difference occurs in the biomass consumption. It can be seen that almost all the “Other and unknown” energy source reported in official publications is met by biomass driven plants in the developed model. Difference in CO₂ emissions is 1.27% and thus, the technical side of the system is modelled in a representative way. To summarize, the figures in total do not vary significantly from the values from the official data. Hence, based on the modelled system, the developed optimization model is considered to be validated.

4.2. Price calculation of DH piping

A quantitative description of the steps presented in section 2.4, as well as the final results of the nominal diameter and the piping price, are given in Table 12.

To validate the estimation, a comparison with other sources was performed. For example, the Danish Energy Agency [60] suggests the price of 18–22 k€/Tj² for the conventional DH network, while

authors in Ref. [61] used the similar price of 20 k€/Tj for the conventional DH network in their study. Using the price for the conventional network, results within the same order of magnitude are obtained.

4.3. Results of the case study for the current state of Sønderborg's energy system

The heat generation results of the first five cases, the ones that assess the impact of interconnecting the currently disconnected DH systems in the Sønderborg municipality, are presented in Fig. 2. Please refer to Table 5 in order to see the order of connection of the different DH systems.

For simplicity, all the gas fired CHP plants (5 in total), gas boilers (5), biomass boilers (2) and solar DH plants (3) production are reported together in the figure.

After interconnecting Sønderborg (town) and Augustenborg DH systems (case II), the heat production from gas CHP plants, gas boilers and electric boilers decreased, while the heat generation from biomass boilers increased. The generation from solar DH plants and the waste CHP plant remained the same, at the maximum utilization rates.

Adding an interconnection to the Broager DH system (case III) caused further decrease in gas boiler generation, while the biomass boilers produced a significantly higher amount of heat. This is the same pattern as in case II. Generation of heat from the electric boiler slightly rebounded compared to the second case, while the solar DH and waste CHP plants are still being utilized at the maximum levels.

In case IV, an interconnection to the Gråsten DH system has been added. It is interesting to note here that no major changes in the heat generation occurred compared to case III. The reason is that the biomass boilers that were preferred over the gas boilers in the previous cases are already maximally utilized in the peak times and the peaks in the demand still had to be met by the gas boilers. It can be concluded that the increase in the utilization of biomass boilers will happen only when interconnecting with a DH system

Table 12
Results of the piping price estimation.

	Case II	Case III	Case IV	Case V
Max heat capacity [MW]	142.26	142.26	122.90	18.00
Max mass flow [kg/s]	849.39	849.39	733.93	107.57
Max volume flow [m ³ /s]	0.85	0.85	0.73	0.11
Flow speed [m/s]	3.00	3.00	3.00	2.00
Cross area of the pipe [m ²]	0.28	0.28	0.24	0.05
Pipe diameter [m]	0.60	0.60	0.56	0.26
DN [mm]	600.56	600.56	558.26	261.76
Pipe price [€/m]	1400.00	1400.00	1297.00	747.00

² Taking into account description in the footnotes of Ref. [60], and accounting for the usage of single piping technology, the cost of 20 k€/Tj can be expressed as 523 €/m. However, those costs also include smaller branch pipes which reduce the cost per meter of piping as they have lower diameters than the main piping. It could not be exactly distinguished between costs for main piping and branch piping from the reference.

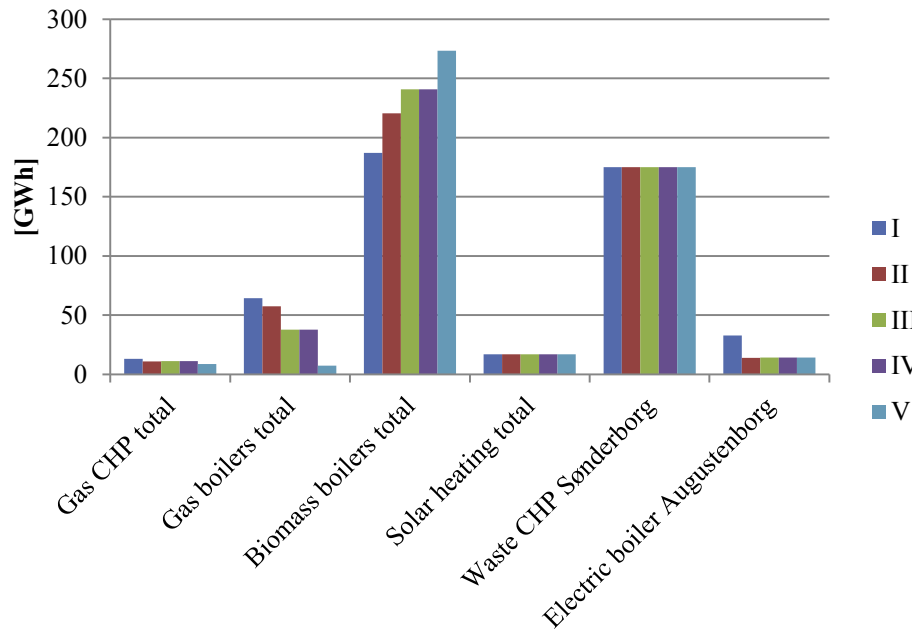


Fig. 2. Heat generation in DH in different cases.

that does not have a biomass boiler in its generation portfolio.

Finally, case V showed that the gas CHP plant and the gas boiler in Nordborg DH system reduced their outputs upon interconnecting the Nordborg DH system with the rest of the DH network in the municipality. This heat demand was instead met by the biomass boilers from Sønderborg and Gråsten. As in all the other cases for the reference year, waste CHP and solar DH outputs remained the same as in the previous cases.

The total system costs, primary energy consumption and CO₂ emissions are presented in Fig. 3. It can be observed that with every new interconnection of DH systems, the total system costs and CO₂ emissions decrease, while the primary energy supply slightly

increases in case II and remains approximately constant in other cases. The reason for the slight increase in PES is that the heat production from the gas boilers is replaced by heat production from the biomass boilers which have a slightly lower efficiency. Furthermore, upon the interconnection of DH grids additional losses in the heat transmission grid of 1.5% of the total heat demand in the municipality need to be compensated for in the model.

The largest CO₂ reductions occurred in cases II and V, a decrease of 2% and 1.2%, respectively. Those are the cases in which a significant amount of heat production from the gas boilers is replaced by the production from the biomass boilers. In total, CO₂ emissions reduced by 3.9% between cases I and V. It is worth mentioning

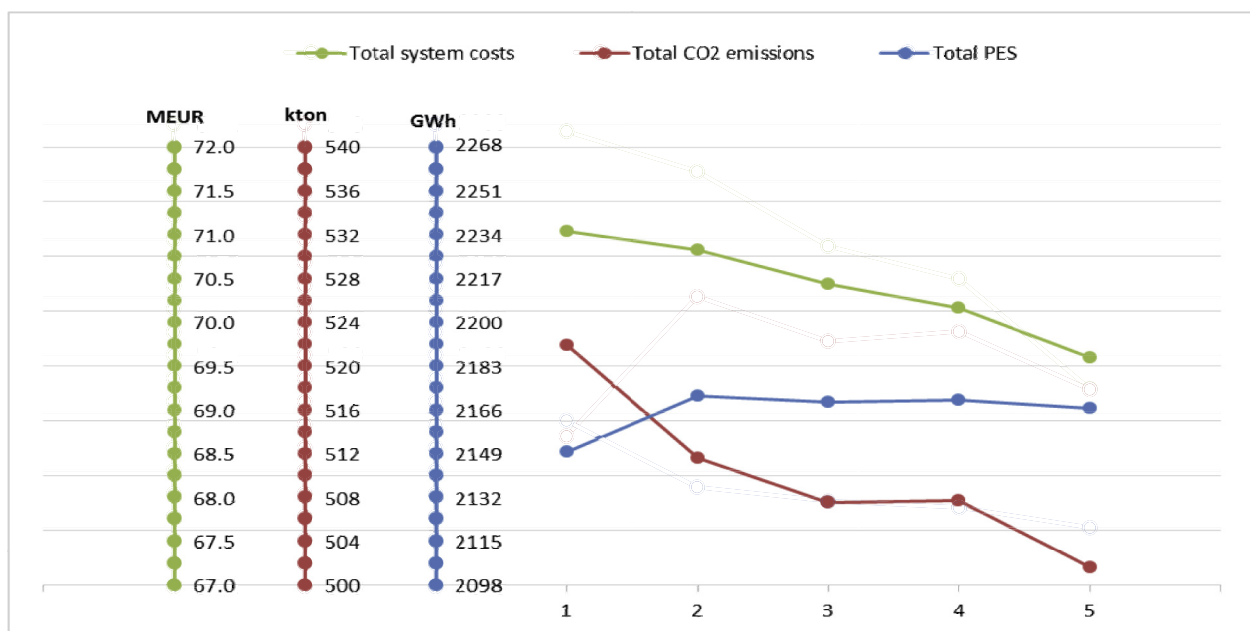


Fig. 3. Total system costs, CO₂ emissions and primary energy supply in the cases I-V.

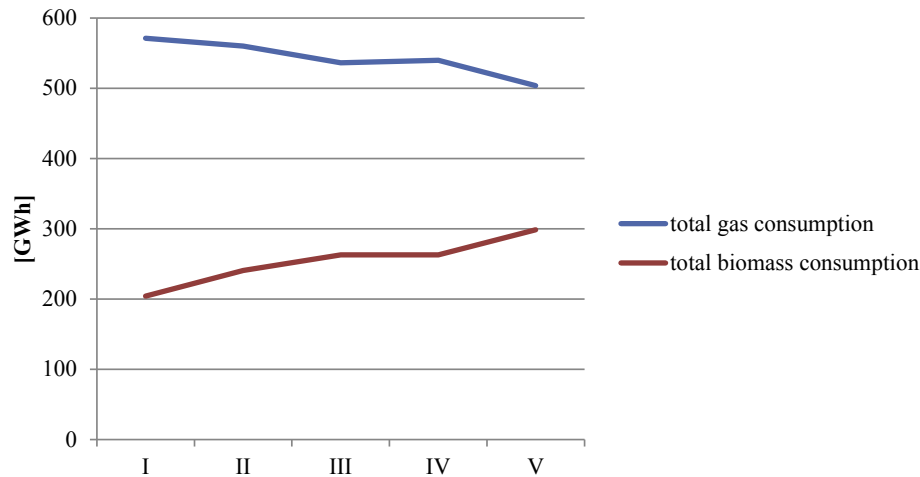


Fig. 4. Total gas and biomass consumptions in the first five cases.

again that the imported electricity has a CO₂ intensity of 0.478 tCO₂/MWh in the year 2013, while biomass is considered as CO₂ neutral.

In general, the presented five cases showed that the running costs of the biomass boilers are lower than those of the gas driven and the electric boilers. Furthermore, in the energy system of 2013 the operation of the gas fired CHP plants with the electricity sold on the electricity spot market has replaced by the biomass driven heat only boilers. The cheapest options for the generation of heat are the solar DH systems and the waste CHP plant. Those plants were maximally utilized already in the reference case (case I), where no additional interconnections were made.

The reason for falling CO₂ emissions upon the subsequent interconnections of DH systems can be seen in Fig. 4. Increasing the heat generation levels from biomass, while reducing the heat production levels from the gas driven plants, can be directly linked to the falling CO₂ emissions.

The economic results of the investment can be seen in Table 13. For the chosen discount rate and the system in the year 2013, investments are profitable for cases II and V, while cases III and IV have a negative NPV value.

It is important to emphasize here that the chosen discount rate and the lifetime of the project are factors that significantly influence the economic results. An additional economic indicator such as IRR can therefore reveal otherwise hidden profitability information. As the investment in transmission piping is considered to be an investment in the infrastructure itself, the chosen project lifetime was set to be the same as the infrastructure lifetime, i.e. 40 years. This value was confirmed in both technology datasheet issued by the Danish Energy Agency and Energinet.dk (the Danish

TSO) [60] and the Stratego Project carried out by different partners [61]. Furthermore, the discount rate of 4% was chosen as a recommendation from the Danish Energy Agency. If one would like to choose different discount rate, IRR presents a good indicator of the discount rates at which the investment would break-even.

The cash flow of the investments is presented in Fig. 5.

It can be seen that the investment in the case V (interconnection between Nordborg DH and other DH systems) was recovered the quickest, as well as that it was the most profitable investment, having the largest NPV value during the project lifetime. The slope of curves reveals that the chosen discount rate of 4% has a significant impact on the present value of future income that will be achieved in the later stages of the project lifetime, diminishing a long-term income. This is another example of the importance of setting the right discount rate.

4.4. Results of case study for the energy system in 2029

Case studies VI and VII were modelled upon the implementation of planned capacities of new energy plants by the year 2029 as stated in Table 6. Case VI corresponds to the five DH systems without any interconnections, while case VII corresponds to the system with interconnected DH systems. Case VIII presents case VI supplemented with the industrial waste heat from the nearby tile works factories, while case IX presents the fully integrated DH system (the system of case VI) supplemented with the industrial waste heat.

Compared to the current energy system of the municipality, the system in 2029 is dominated by electricity and gas exports, which is the result of planned investments in renewable energy sources, mainly in wind, PVs and anaerobic digestion technologies.

The difference between the power and gas sectors of Sønderborg municipality in the reference year and the year 2029, according to the official development plans, can be seen in Fig. 6.

The generation of heat by different energy plants before and after interconnecting the DH systems for the year 2029 is presented in Fig. 7. Please note that the order of the presented cases in Fig. 7 is VI, VIII, VII, IX, in order to be easier to compare cases without interconnected DH systems (cases VI and VIII) and two cases with fully interconnected DH systems (VII and IX).

After interconnecting the DH grids, the large scale heat pump and the geothermal heat plant (which is coupled with a biomass-fired absorption heat pump) had a much larger utilization rate, compared to the systems without interconnections. On the other

Table 13

Economic results of different cases – note that savings for each case were calculated as the difference in total system costs in comparison to the previous case. Thus, savings in case II present the difference in total system costs between case II and case I. Other cases follow the same principle.

	I	II	III	IV	V
Total system costs [M€]	70.969	70.75	70.332	70.04	69.432
Difference (savings) [M€]	Reference	0.219	0.418	0.292	0.608
Pipe length [m]	–	3000	11,000	6000	13,000
Specific pipe cost [€/m]	–	1400	1400	1297	747
Pipe cost [M€]	–	4.2	15.4	7.782	9.711
NPV [M€]	–	0.13	–7.13	–2.00	2.32
IRR	–	4.21%	0.41%	2.15%	5.54%
Discounted payback time [years]	–	37.16	–	–	25.97

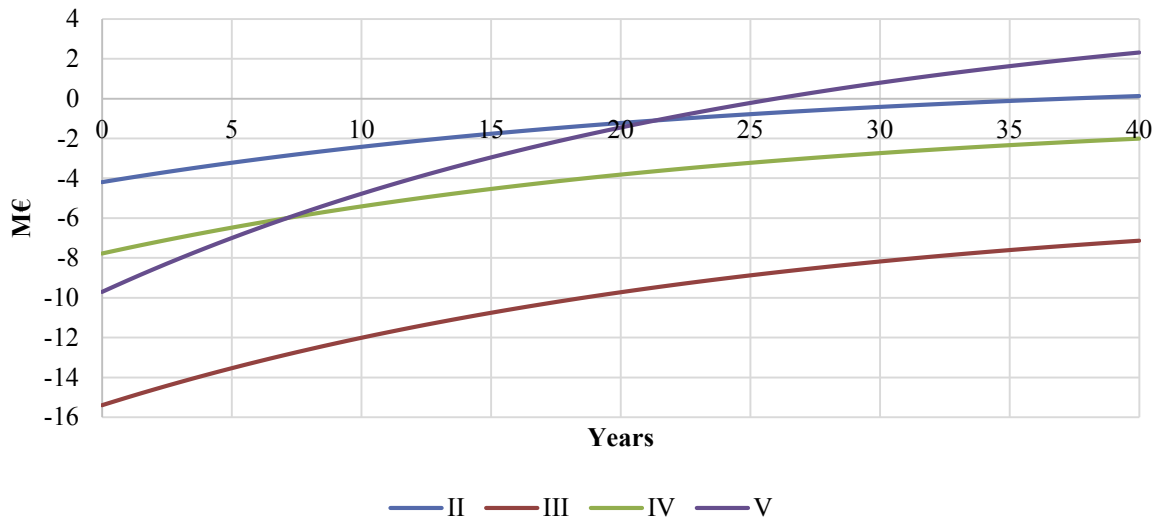


Fig. 5. Cash flow of investments in different cases.

hand, the electric and biomass boilers decreased their utilization rate significantly. Moreover, the generation from the gas driven CHP plant reduced while the gas heat only boilers were not utilized at all. The solar heating DH plants and the waste CHP plant are being maximally utilized in all the cases.

In case VIII, industrial waste heat available in Broager and Gråsten DH systems replaced the generation of gas and biomass boilers, as well as the gas CHP plant. In the interconnected DH system (case IX), industrial waste heat caused a slight reduction of heat generation in the large scale heat pumps, biomass boilers and geothermal heat source coupled with the absorption heat pump.

It is interesting to observe the operation of the heat pump in relation to the wholesale electricity prices which is shown in Fig. 8. A negative correlation between the two variables is observed; as the electricity price goes down, the heat generation from heat pumps goes up and vice versa. In the interconnected DH system, a larger number of customers can be supplied by a technology existing at the specific location. Therefore, the large scale heat pump can be better utilized, increasing the amount of electricity demand in the periods of lower electricity prices.

The differences in the economic and technical indicators in the four cases carried out for the year 2029 are presented in Fig. 9.

It can be seen that in the year 2029 (cases VI and VII), an interconnection of all the DH systems is beneficial according to all three indicators. Furthermore, both cases with the industrial waste heat fed into the DH grid showed better results in all three indicators presented. Note here that the investment in the waste heat recuperators and the connecting piping to the nearest DH system were leveled during the lifetime of the plant and are included in the reported total system costs.

Comparing case VII to case VI, the savings in PES amounted to 9.5%, the CO₂ emissions were 11.1% lower and the total system costs were reduced by 6.3%. Detailed economic results of the investment in the transmission piping and the accompanying economic indicators are presented in Table 14.

Significantly better results are achieved when the industrial waste heat was fed into the DH grid even in the geographically distributed DH systems (case VIII), as it can be seen in Fig. 9. However, compared to the distributed DH grids, in the case of fully interconnected DH grid (case IX), PES was reduced by 7.2%, CO₂ emissions by 8.9% and total system costs by 5.1%. Thus, the best outcome was reached in the last case, with the fully interconnected DH system, as well as with the industrial waste heat fed into the grid.

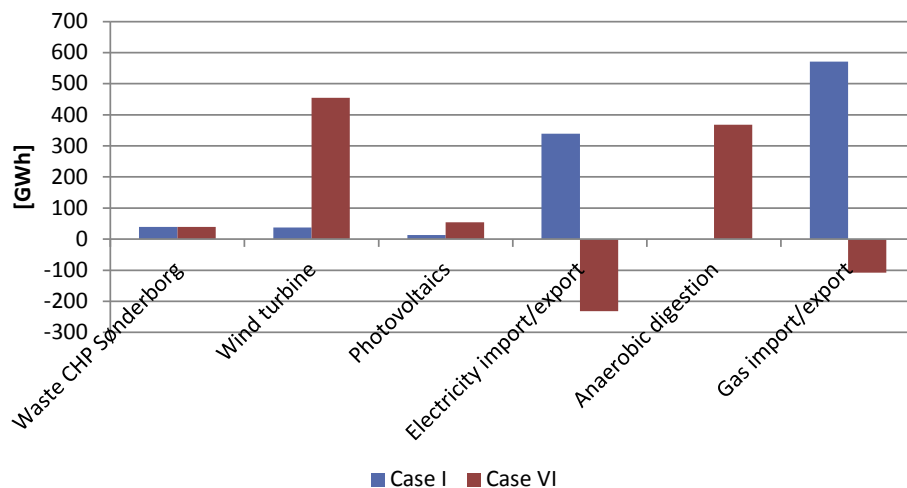


Fig. 6. Generation of the power and gas sectors of the Sønderborg municipality. Negative values denote energy export from Sønderborg municipality.

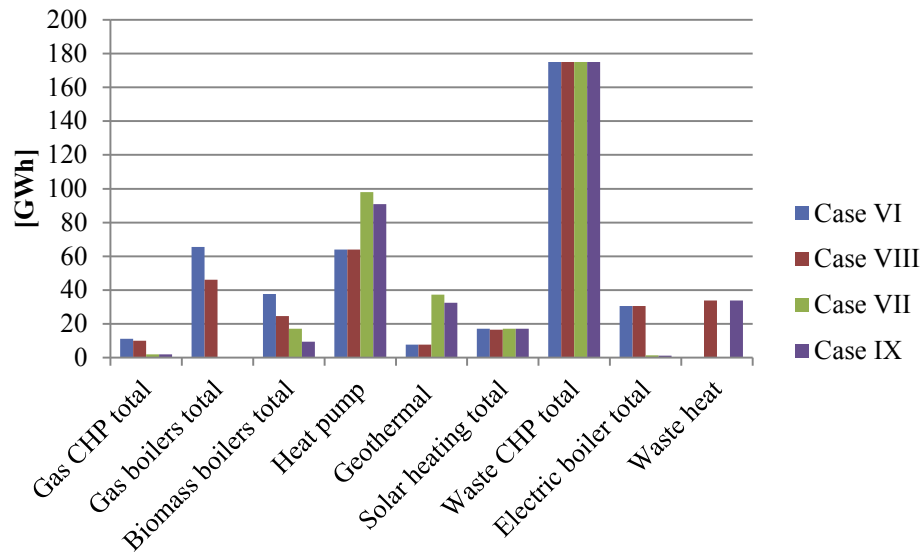


Fig. 7. Heat generation from different sources in the year 2029.

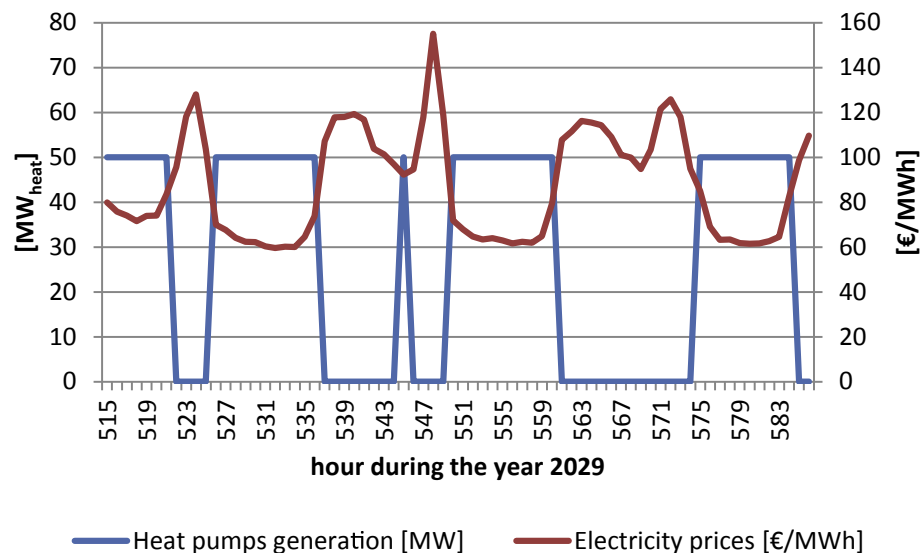


Fig. 8. Heat pumps operation (heat generation capacity) in relation to power prices on the wholesale market during three days - case VIII.

4.5. Sensitivity analysis

In order to check the robustness of the model, a sensitivity analysis for different parameters was carried out. The most important parameter for the feasibility of the investment in interconnection of the DH systems is the piping price. Hence, the impact of varying piping price has been checked and the impact on economic indicators of investment can be seen in Fig. 10. The sensitivity analysis was carried out for case VII (fully interconnected DH grids in the year 2029) as this was the best performing case without considering waste heat from industry.

Fig. 10 reveals that NPV and dynamic payback time have an almost linear relationship with the change in total piping costs. On the other hand, the IRR curve clearly shows that for a reduced piping cost the internal rate of return rose much steeper than it reduced in the case of increased piping cost. This behaviour can guide future researchers to try to find further economies of scale when calculating interconnections of different DH systems as a

relatively small reduction in piping investment can cause a significantly better rate of return.

Fig. 11 shows how the NPV changes when the discount rate grows and drops. It can be seen that the increase of NPV, for lower discount rates, is much steeper than the decrease of NPV, for the case of higher discount rates. This leads to the conclusion that even small support, in a form of a lower discount rate, can improve the economic performance of this kind of investment significantly, whereas higher rates do not influence the NPV to such extent. It is once again shown that the IRR for this case is 13.85% (the point where the NPV equals zero).

Furthermore, sensitivity analysis was carried out for the following parameters in the cases developed for the year 2029: CO₂ price, heat storage size, electricity and biomass prices. However, none of these changes caused the total system costs to change by more than 1%, even for changes in the selected parameters of up to 50%.

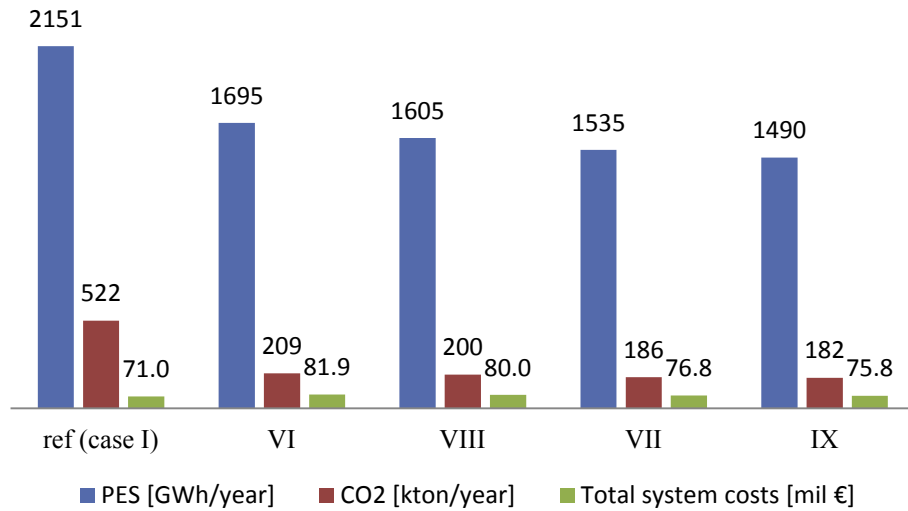


Fig. 9. Results of cases VI, VIII, VII and IX and comparison with the reference case.

Table 14

Economic results for the system in the year 2029.

	VI	VII
Total system costs [M€]	81.93	76.77
Difference (savings) [M€]	0	5.167
Pipe length [m]	0	33,000
Pipe cost [M€]	0	37.093
NPV [M€]		65.18
IRR		13.85%
Discounted payback time [years]		8.63

5. Discussion

Firstly, when building an optimization model, it can be of crucial importance what type of optimization is chosen. For example, Ommen et al. modelled an energy system consisting of CHPs, heat pumps and boiler units with the objective function to minimize the total running costs [62]. They have examined three different optimization types, linear programming (LP), mixed-integer

programming (MIP) and non-linear programming (NLP) and showed that the operation times of different plants differed significantly when different optimization methods were chosen. They concluded that MIP and NLP better represented the real operation; however, they acknowledged the enormous increase in computation time when using the latter two methods compared to the LP. Furthermore, they optimized only according to the running costs, which made their number of variables lower than in the model developed in this paper. In order to cope with the enormous number of variables, and adopting an hourly time-resolution to represent intermittent energy sources in a satisfactory way, the authors of this paper decided to use a linear continuous optimization method which assured that the problem is solvable in the reasonable amount of time, in the same time keeping the major important relations that represented the modelled energy system in a realistic way. The latter was proven when validating the model for the reference year.

There are different energy modelling tools available under different licenses that are suitable for analysis of district heating

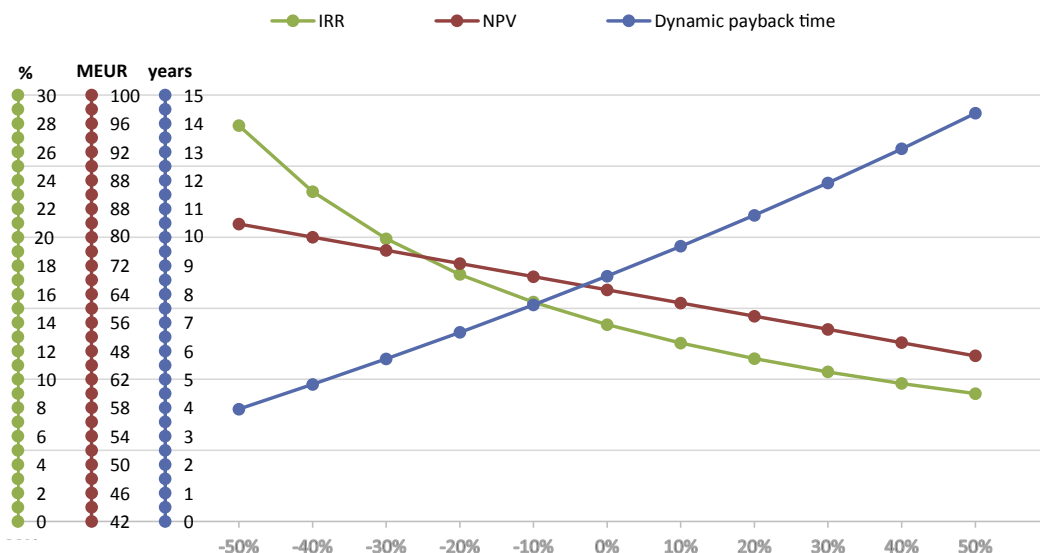


Fig. 10. Sensitivity analysis carried out for the piping price of case VII.

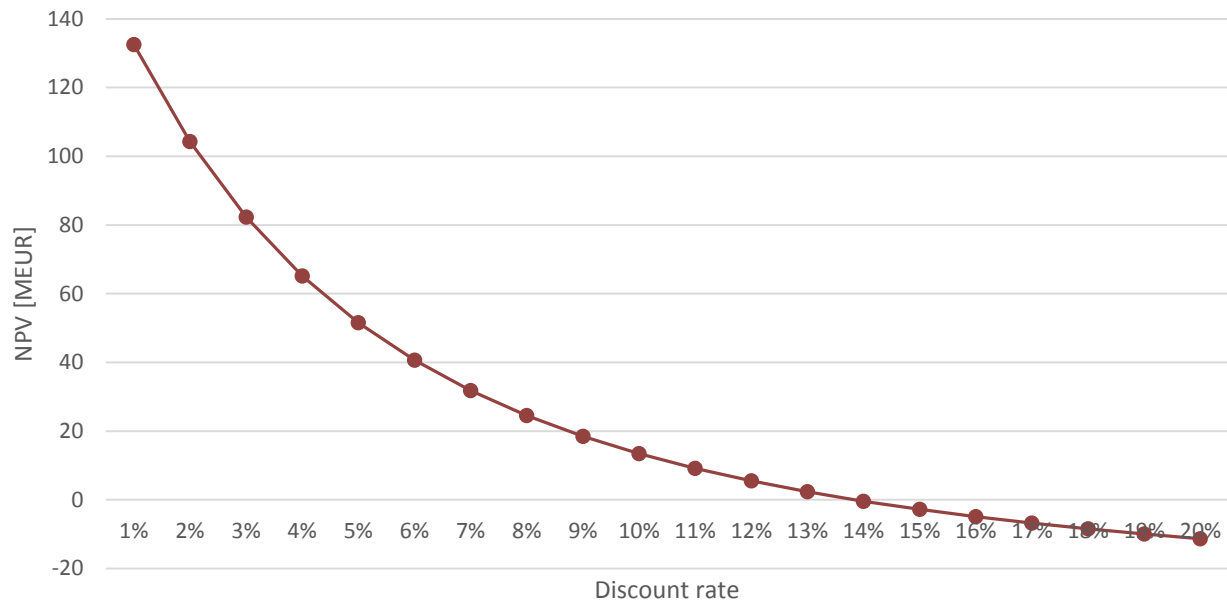


Fig. 11. Impact of change in the discount rate on the NPV.

systems. The overview of the energy modelling tools was done in Ref. [63]. Two types of software that were often used for district heating systems are Termis [64] and EnergyPRO [65].

Termis software receives live data from SCADA system as well as forecast information about weather conditions through the data interface. Based on the latter data it predicts future consumption up to three days in advance. It is a good software for simulating the network, running short-term optimization, maintenance planning and detecting failures. It can be used to optimize supply and/or return temperature, pressure, flow, etc. Compared to the model developed in this paper, one can note that it is better suited for short-term optimization, used for real-time operation scheduling, while the developed model is better suited for detecting system impacts of installed capacity changes within the system. Furthermore, Termis cannot optimize new capacities that could be potentially beneficial for reducing business-economic or socio-economic costs. Finally, it focuses on district heating grid, without taking into account other energy sectors such as the power and gas sectors.

EnergyPRO is a modular input-output simulation tool that can be used for different purposes such as calculating the optimal operation of the energy plant, making detailed investment analysis, modelling industrial cogeneration and trigeneration systems, simulating energy plants participating on different electricity markets and analyzing the interaction between separate energy plants [65]. Some examples of large scale systems modelling are simulation of the whole energy system for the city of Pecs, Hungary [66], simulation of the Tallinn district heating network [67] and for a theoretical case representing the typical Danish DH system [68]. In all the mentioned cases it was only used to calculate the operating costs of the system, without taking into account the capital expenses. Investment analysis carried out by the model usually focuses on the single plant investment, as opposed to the total socio-economic costs of the system. Furthermore, similarly to Termis, it is also a simulation tool, meaning that the installed capacities need to be set by the user prior to the model run. Hence, the capacity optimization can only be carried out by manual iteration procedure. Thus, the model developed in this paper with its current features, as well as possibilities that were not used in this paper due to already lengthy case studies, such as constraining the biomass

consumption, CO₂ emissions and optimizing new investments by taking into account sunk costs of already made investments present a valuable upgrade from the described two models. Finally, the model developed in this paper incorporates investments as a part of socio-economic costs, inclusion of sunk costs in the model was possible. These are the costs of current investments that already occurred and cannot be recovered anymore. Thus, potential new investments, such as connecting piping that was modelled in this case study, need to be economically feasible not only comparing the running costs, but also the investments costs of already existing technologies, too. This can significantly alternate the investment results. One can notice in our results that upon interconnection of district heating grids (cases VII and IX), gas boilers were not dispatched during the year while electric boilers and gas CHPs had very low utilization rate. However, as these investments were already made, they were included in the calculation of the total socio-economic costs and investment in piping had to compete with these costs, too. The potential of inclusion of sunk costs in the model opens a possibility to make more detailed economic analysis of the possibility to add emerging technologies in the current energy systems in a future research.

In order to show important differences between the current energy system and the envisaged future energy system, the one that is targeted with the official plans and roadmaps, nine different case studies were developed. Five case studies were developed for the reference year, in order to validate the model itself, as well as to present differences when connecting different DH grids, each one with their own specifics in energy supply and demand. It is important to note from these cases that no general correlation between the diameter of the transmission pipe, length of the piping and the viability of the investment could be reached. This shows that it is important to approach each local energy system separately and that no general conclusions should be made from a single case. This conclusion is in line with the previously published work, such as [15] and [16], in which many different cases showed that the economic and technical figures of integration of DH systems is dependent on the type of energy producers present in the DH system. Moreover, it was showed from these cases that the energy supply mix of the DH system being integrated with the interconnecting transmission pipe is more important than the distance

between the DH systems itself. The latter also points to the possibility that some of the DH suppliers could end up with much lower utilization rates of their plants in case of new interconnections to their grid. This could cause an opposition to the interconnection of the grids, even if the society as a whole would benefit from it.

Two interconnections were feasible and two were not for the energy system in the reference year. The best economic results were obtained in case V, although the distance of Nordborg DH to the rest of the system was the largest. The reason for this is the energy supply mix of Nordborg DH system, being heavily focused on expensive gas fired heating plants. Case II was the other economically beneficial case in the reference year. The connected area was previously supplied by a gas fired CHP and a gas boiler, as well as electric boiler. Furthermore, the distance of the transmission piping was the lowest in case II of all the cases. Hence, it can be concluded that savings in the running costs due to the lower utilization of gas driven plants and electric boiler were larger than the investment in the transmission piping. On the other hand, cases III and IV had biomass boiler and solar district heating plants incorporated in the system, besides the gas fired technologies. As these technologies were not utilized significantly more than in the interconnected systems than in the geographically the distributed systems (as they reached maximum capacity quickly), savings in running costs could not recover the investment in the transmission piping. However, IRR values of all the cases were positive which means that changing the discount rate could also change the economic feasibility of the investment. As investments in interconnections are long-term and low-risk infrastructure projects, in the current economic circumstances of the European financial market, one could argue for choosing a lower discount rate than the one proposed by the Danish Energy agency (4%) that was used here. However, the somewhat ambiguous and vague results of the economic indicators of the current system can significantly change if the proposed changes for the future energy system in Sønderborg will take place as planned.

To take into account the latter reasoning, two case studies (cases VI and VII) were developed following the official publications, reports and roadmaps of the stakeholders involved into the transition of the Sønderborg municipality to a net zero carbon energy system. The energy import dependant system of today is envisaged to become a net exporter of both electricity and gas, while achieving a carbon free heating system in the same time. In order to achieve this, a much higher capacity of intermittent renewable energy sources will be a part of the energy mix in the year 2029. By interconnecting DH systems, the whole energy system can become cheaper and more flexible. This is shown in case VII, in which the discounted payback period for the investment in the infrastructure was only 8.62 years. An important conclusion here is that the infrastructure investment that is not clearly seen as economically beneficial in the system of today can be a very beneficial investment in the future energy system. Thus, it is important to take into account a future development of the energy system when calculating feasibility of the specific infrastructure investment, as focusing only on the present energy system can lead to the erroneous decisions for the future. One can note from Fig. 8 that the large scale heat pumps operated in periods of lower electricity prices and not in periods of relatively high electricity prices. This finding shows that heat pumps are suitable to take advantage of the relatively low power prices that occur when large amount of intermittent power generation pushes the electricity prices down or when there is a lack of demand for electricity. This should also be a guide for any consideration of energy supply in future smart energy systems; detecting if the possibilities of integration of DH systems positively impacts the integration of fluctuating RES in the power sector. Such a realization could not be made by solely focusing on the power

sector. The latter also confirms that the integration of power and heat sectors leads to a technically better system that is able to integrate the same amount of intermittent sources in a cheaper way, with less harmful emissions, and in a more energy efficient way.

Furthermore, due to different laws, privacy of business data and other hindrances, the amount of industrial waste heat potential is often hard to assess, which leaves it outside of the focus of the research or official plans for energy transition. Cases VIII and IX were developed specifically for that purpose and they both showed significant primary energy savings, a CO₂ emissions reduction and lower socio-economic costs. It is important to note here that all three indicators improved already when feeding the industrial waste heat into the distributed DH systems (case VIII), becoming even better when the DH grids were fully interconnected (case IX). Hence, more emphasis should be put on future research in the industrial waste heat potential, as these potentials can be relatively simple to integrate, while beneficial in both technical and economic terms. Finally, different pricing mechanisms of DH systems should be developed that would fairly value the waste heat in different periods of time as this heat can be competing with the waste incineration plants, geothermal plants and others. For the combination of many prosumers in DH systems, with a more complex energy supply portfolio, especially if DH systems would in general start to be physically interconnected more often, the constant average yearly price per energy unit in different periods will make it more complex to bolster energy integration of prosumers.

Some more technical statements can be made by reflecting on all the cases. Generally, CHP plants do not seem to have a suitable economic justification for large-scale operation, although these types of plants are generally considered as very energy efficient and capable of reducing CO₂ emissions significantly. Partially the reason for this behaviour can be found in the relatively high gas prices in the reference year (2013). It would be probably a more beneficial situation if biomass fired CHP plant would be installed instead of some (or all) gas fired CHP plants. Furthermore, each subsequent DH grid interconnection caused a decrease in the production of gas boilers and an increase in the generation of biomass boilers. Moreover, biomass boilers also replaced a part of electric boiler generation, as shown in case II.

In the case of geographically distributed DH systems, industrial waste heat replaced part of the production from gas boilers, biomass boilers and gas CHPs. In the case of fully interconnected DH grids, the waste heat replaced a part of biomass boilers generation, as well as heat pump and geothermal heat source coupled with absorption heat pump. In the latter case the gas boilers did not produce any heat at all. As the waste heat not fed into the DH grid would be wasted otherwise, all of these changes in generation of different heat producers caused improvements in both economic and technical indicators.

Sensitivity analysis showed that the only significant parameter is investment in the piping itself. Especially important is the finding about the IRR behaviour when the piping cost was changing. Reductions in the piping costs caused IRR to ascend much steeper compared with descend of the same indicator when the piping investment cost was increasing. Hence, it can be concluded that the modelled system is relatively robust and that economies of scale should be sought for when calculating the piping investment, as a relatively small decrease in the piping price could increase the viability of the potential investment significantly, measured with the IRR indicator. One should also note that piping distances between different DH systems were assumed to be straight lines. However, a detailed feasibility study should be carried out to check whether this assumption is viable. If not, the economic indicators would be less beneficial, as shown by the sensitivity analysis

presented in Fig. 10, although they would remain positive in the year 2029 even for the increase in piping investment of 50%.

When focusing on differences in CO₂ emissions and the total system costs of cases I and V and cases VI and VII, it is important to notice the necessity of a geographically correct representation of the physical boundaries of the DH systems. Modelling all the DH systems as a single point systems, in an aggregated manner, would lead to the underestimation of both CO₂ emissions and socio-economic costs. To clarify this issue further, the district heating system represented in an aggregate manner is the same system as in the case V, while the truly represented district heating system of today is the system in the case I. Thus, the difference between the results of these two cases can be seen as the error in representation of the DH systems as an aggregated one.

The results of this paper can be compared with other similar case studies. In the case study for local DH in Sweden, carried out by Gebremedhin and Moshfegh, the results showed that expanding the system boundary allowed different actors to participate on the heat market [18]. However, the possibility of increased cogeneration plants operation by connecting DH systems was not confirmed [18]. The latter finding was the same in our case study, while the former one is somewhat different. In the case study carried out in this paper, a lower number of heat producers were being dispatched but more often, as more efficient plants could be utilized to deliver the energy for wider range of consumers. The results of the case study carried out by Karlsson et al. showed that connecting the separated systems into one large system enhances the possible profits when looking at the total system, resulting in the payback times between two and eleven years [19]. This paper supports this conclusion as the discounted payback period for the year 2029 (case VII) was 8.63 years in the case of fully interconnected systems. Kimming et al. carried out four scenarios based on biomass fired heating plants, with different distribution distances, and compared it with a reference case, in which a gas driven heating plant was being utilized [21]. They concluded that the biomass based options, even when increased transportation distances are taken into account in life-cycle analysis, had lower climate impact compared to the gas driven heating plant [21]. The latter finding was confirmed by our case study, as upon interconnection of the DH systems the biomass boilers were utilized more often. This reduced the CO₂ emissions compared to the case of the disconnected DH systems, where more utilization of gas fired plants resulted in higher CO₂ emissions.

6. Conclusions

The following main conclusions can be drawn from the current model and case study:

- For the current energy systems, two out of four DH interconnections are economic feasible with the IRR of 4.21% and 5.54%. Compared with the chosen discount rate of 4%, two other investments were not feasible as their IRRs were 0.41% and 2.15%. After the last interconnection was set in place, the total socio-economic costs were 2.2% lower than in the reference case.
- Connecting all the five DH systems in the energy system anticipated for the year 2029 has a payback time of only 8.63 years. Moreover, the investment proposed leads to the savings in PES amounting of 9.5%, 11.1 % lower CO₂ emissions and reduced total system costs by 6.3%.
- In the case of industrial waste heat being available for supplying heat to the DH grid, in the case of fully interconnected DH grid (case IX), PES was reduced by 7.2%, CO₂ emissions by 8.9% and total system costs by for 5.1% compared to the industrial waste

heat being fed into distributed DH systems. Thus, the best outcome was reached in the last case, with the fully interconnected DH system, as well as with the industrial waste heat fed into the grid.

- There is no correlation between the length of the interconnections or pipe diameters and the economic indicators of the investments. Thus, the investment in interconnection depends on the energy mix of the DH supply plants being interconnected.
- Large-scale heat pumps, with the average electricity price levels similar to current ones, completely replace the production of all the boilers, including the electricity, biomass and gas ones.
- Interconnecting the DH systems is beneficial in both the current energy system and the anticipated system in the year 2029. However, in the future system dominated by the generation of electricity from intermittent sources in the power sector, the benefits of interconnecting the DH systems are far greater according to all three indicators: total system costs, primary energy consumption and CO₂ emissions. Connecting DH grids brings more flexibility to the system, making it cheaper, less environmentally harmful and more energy efficient to integrate intermittent energy sources in the power sector.

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Abbreviations

BAU	Business-as-usual
CHP	Combined Heat and Power
COP	Coefficient of Performance
COP21	2015 Paris Climate Conference
DEA	Danish Energy Agency
DH	District Heating
EU	European Union
GHG	Greenhouse Gas
IEA	International Energy Agency
IRR	Internal Rate of Return
LP	Linear Programming
MB	Megabytes
MIP	Mixed-Integer Programming
NLP	Non-Linear Programming
NPV	Net Present Value
O&M	Operation and Maintenance costs
PES	Primary Energy Supply
RAM	Random Access Memory
RES	Renewable Energy Source
TB	Terabytes
TSO	Transmission System Operator
RAM	Random Access Memory
RES	Renewable Energy Source
TB	Terabytes
TSO	Transmission System Operator

Nomenclature

A_p	cross area of the pipe, m^2
bio_cap	Maximum allowed biomass consumption in the modelled system, MWh
$CO2_cap$	Maximum amount of emissions allowed in the system, ton
$CO2_inten_j$	CO_2 intensity of a certain technology or energy within the system boundaries, ton/MWh
$CO2_inten_k$	CO_2 intensity of a certain technology or energy coming in or out of the system boundaries, ton/MWh
$CO2_j$	Costs of CO_2 emissions, €/ton
c_w	specific heat capacity of water, $4.187 \text{ kJ}/(\text{kg} \times \text{K})$
$dies_dem$	Diesel demand, MWh
$dies_imp_k$	Price of import of diesel in a specific hour, €/MWh
dis_rate_i	Discount rate of the technology i , %
DN	Nominal diameter of the pipe, mm
el_dem	Electricity demand, MWh
$el_imp_exp_k$	Price of import or export of electricity in a specific hour, €/MWh
$fix_O\&M_i$	Fixed operating and maintenance costs of energy plants, €/MW
$fuel_j$	Fuel cost of specific energy type, €/MWh _{fuel}
gas_dem	Gas demand, MWh
$gas_imp_exp_k$	Price of import or export of gas in a specific hour, €/MWh
$heat_level_r$	Heating energy content stored in the energy storage, MWh
$heat_dem_t$	Heat demand in district heating grid t , MWh
inv_i	Total investment in technology i , €
lev_inv_i	Levelized cost of investment over the energy plant lifetime, €/MW
$lifetime_i$	Lifetime of the technology i , years
\dot{m}_{max}	maximum mass flow of the water transferred through the pipes, kg/s
$petr_dem$	Gasoline demand, MWh
$petr_imp_k$	Price of import of gasoline in a specific hour, €/MWh
$q_{v,max}$	maximum volume flow of the water transferred through the pipes, kg/s
t	the number of geographically separated DH systems; number of DH grids = 1, 2... t
$var_O\&M_j$	Variable operating and maintenance costs of energy plants, €/MWh
v_f	flow velocity, m/s
x_i	Capacity variables of energy plants, transmission grid and gas grid, MW
x_j	Generation capacities of energy plants (8760 variables for each energy plant, representing the generation in each hour during the one year), MWh
$x_{j,EL}$	Hourly generation of technologies which generate electricity
$x_{j,EL,biomass}$	Hourly generation of technologies which generate electricity and are driven by biomass
$x_{j,EL,gas}$	Hourly generation of technologies which generate electricity and are driven by gas
$x_{j,EL,other}$	Hourly generation of technologies which generate electricity and are driven by other fuel types
$x_{j,heat}$	Hourly generation of technologies which generate heat
$x_{j,heat,gas,t}$	Hourly generation of technologies which generate heat, are driven by gas and operate in the DH system t
$x_{j,heat,biomass,t}$	Hourly generation of technologies which generate heat, are driven by biomass and operate in the DH system t

$x_{j,heat,gas,t}$	Hourly generation of technologies which generate heat, are driven by gas and operate in the DH system t
$x_{j,heat,other,t}$	Hourly generation of technologies which generate heat, are driven by other fuel types and operate in the DH system t
$x_{j,heat,storage_ch,t}$	Hourly charge of heat to the heat storage operated in the DH system t
$x_{j,heat,storage_dis,t}$	Hourly discharge of heat from the heat storage operated in the DH system t
x_{j,an_dig}	Generation of gas after CO_2 removal in anaerobic digester
x_k	Import or export across the system boundaries of different types of energy (8760 variables per one type of energy, representing the flow in each hour during the one year), MWh
ΔT	water temperature difference, K
η_j	Efficiency of technology, MWh_{energy}/MWh_{fuel}
φ_{max}	maximum heat capacity transferred through the pipes, W
ρ_w	water density, $1000 \text{ kg}/m^3$

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Paper 7 - Utilizing thermal building mass for storage in district heating systems: Combined building level simulations and system level optimization

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Utilizing thermal building mass for storage in district heating systems: Combined building level simulations and system level optimization

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ABSTRACT

Higher shares of intermittent renewable energy in energy systems have raised the issue of the need for different energy storage solutions. The utilization of existing thermal building mass for storage is a cost-efficient solution. In order to investigate its potential, a detailed building simulation model was coupled with a linear optimization model of the energy system. Different building archetypes were modelled in detail, and their potential preheating and subsequent heat supply cut-off periods were assessed. Energy system optimization focused on the impact of thermal mass for storage on the energy supply of district heating. Results showed that longer preheating time increased the possible duration of cut-off events. System optimization showed that the thermal mass for storage was used as intra-day storage. Flexible load accounted for 5.5%–7.7% of the total district heating demand. Furthermore, thermal mass for storage enabled more solar thermal heating energy to be effectively utilized in the system. One of the sensitivity analyses showed that the large-scale pit thermal energy storage and thermal mass for storage are complementary. The cut-off duration potential, which did not compromise thermal comfort, was longer in the newer, better insulated buildings, reaching 6 h among different building archetypes.

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1. Introduction

District heating systems produce heat centrally and distribute it to the end consumers via transmission and distribution pipes. Heat storage can be used when a mismatch between the timing of production and demand for heat occurs. Other solutions include peak boilers that can quickly be dispatched. When comparing heat storage and peak boilers, the former usually has large capital costs and low operating costs, while the latter usually have larger operational costs and lower capital costs.

All buildings, which are connected to district heating systems, have certain thermal capacities for storing heat inside the structure of the buildings. Contrary to the usual heating storage types such as hot water tanks or water pits, the capital costs for the utilization of thermal mass for storage is close to zero, as the building structure

does not have to be modified additionally. Thus, utilizing thermal mass for storage could be an efficient solution for load shifting and/or peak shaving in district heating grids. The objective of this paper is to analyse the potential of utilizing thermal mass for storage in district heating systems in order to reduce the operational costs of the district heating systems by optimally shifting the district heat load. District heating systems are dominated by the peak demand during a few morning hours [1], which results in higher operational costs of the district heating systems.

One of the main findings from a recent review of the district heating and cooling systems has indicated that district energy systems are more efficient than individual heating and cooling systems, based on many projects reviewed across the world [2]. Thermal energy storage was one of the emphasized technologies that has a potential to further increase efficiency into current district energy systems [2]. It has been anticipated that district heating should play an important role in future renewable energy systems [3]. Moreover, authors have concluded that the future smart thermal grids will involve more energy efficient buildings, as well as integration with electricity and gas grids [3]. For the case of future energy system of Denmark, the share of 55–57% of district heating

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in the total heat demand could be cost-effective from the energy system point of view, although significant heat savings in the building sector have been anticipated [4]. Another recent international review of district heating and cooling systems claimed that those systems have strong potentials to be feasible supply options in a future world [5]. An author has reported that large national district heating research projects are being supported in Denmark, Germany, Sweden and China [5]. It was further concluded that heat recovery and heat based on renewable energy sources is larger in the European Union than in the rest of the world [5]. Nevertheless, the future energy system will need to balance out the potential energy savings in the building sector with the renewable energy supply in a cost-effective way. One study showed that the energy demand of buildings could be cost effectively reduced by 12–17% by the year 2015 [6]. The same study has shown that larger savings are to be expected in individual heating areas than in district heating areas.

Thermal energy storage has proven to be a technology that can be beneficial towards the energy efficiency of a building by contributing to an increased share of renewable energy and/or reduction in energy demand or peak loads for both heating and cooling [7]. Thermal building mass for storage could serve as a supplement to already existing storage solutions, such as hot water tanks. The reason for the latter is the low capital costs in thermal building mass storage type, as no physical alterations to the buildings are needed. Many different thermal storage options have been researched and some are already implemented on a large scale. Thermal storage can be realized in several different ways. They can be central (closer to the supply side of the system) or decentral (close to the consumer side of the system). Another division considers the thermodynamic nature of the way heat is stored, i.e. whether it is latent, sensible or thermochemical storage. Seasonal thermal energy storage has been reviewed in Ref. [8] and it was concluded that although it is a promising technology, its cost does not make it applicable to all projects, even less for single family houses. Furthermore, a review of promising candidates for chemical heat storage has been reviewed in Ref. [9], highlighting its significant potential due to the high thermal storage density, but also its low efficiency, special consideration of safety and large initial investment that is required. Thermal energy storages using phase change materials (PCMs) have been reviewed in Ref. [10]. One of the main aspects of PCMs is their low thermal conductivity (usually between 0.2 and 0.7 W/mK), thus requiring the use of complex heat exchanger geometries to obtain required heat transfer rates from latent heat storage containers. Regarding thermal storage building integrated systems, one study reviews it extensively [11]. The authors have concluded that active storage systems in the building envelope could be used when constructing new buildings. The integration of active thermal storage in buildings should be planned during a design phase in order to overcome the problems of availability of space for installations. In the same study, it has been claimed that both commercial and public buildings have huge potential on implementing thermal energy storage in double skin façade as well as in ventilation systems.

The utilization of short term heat storage in the sensible thermal mass of the buildings has been investigated in a number of studies during the last years. The zero investment cost that is required for the utilization of the thermal mass along with the capacity that is available in the majority of buildings in northern climates makes it a promising storage solution. One study of combined thermal energy storage and buildings has also dealt with a potential of using thermal mass of buildings for sensible heat storage [7]. It was concluded that the thermal energy storage can result in increased energy efficiency in buildings, reduced emissions, increased efficiency of HVAC equipment and reduced peak loads in system [7]. It

was further argued that it is important always to fulfil specific demands and conditions that differ from building to building [7]. In a Danish study [12], two residential buildings with different states of insulation and air tightness were examined in terms of heat storage and heat conservation. The findings showed that the potential of the thermal mass depends on many factors (level of insulation, heat emission system etc.) and varies significantly over the season. The poorly insulated building could offer short thermal autonomy or heat flexibility meaning the time where the building can perform without activating a heating system, while the energy efficient passive house had a much higher time constant. This means that large amounts of heat could be shifted for shorter periods of time in poorly insulated buildings. On the contrary, a complete switch-off of the heating system could be achieved in the passive house for more than 24 h without violating the thermal comfort of the occupants.

Demand side management (DSM) can be defined as a modified consumer energy demand through various methods. Usually, the balancing of intermittent generation and load shifting from peak demand hours to off-peak demand hours are the most important targets of the DSM. A study by Ref. [13] investigated the potential of structural thermal mass of a single family dwelling for demand-side management (DSM) equipped with an air-to-water heat pump coupled with low temperature heat emission system, as well as a photovoltaic system in South-eastern Europe. The findings showed that the structural storage capacity has strong potential for shifting peak electricity loads for heating to off-peak hours. The DSM potential was found to be higher for massive buildings than for light-weight buildings.

Furthermore, the interaction between the heating system and the available thermal mass is significant. The authors in Ref. [14] have addressed that even after very short overheating periods, the heating demand for the following hours can be reduced significantly (up to 20%) utilizing the thermal storage capacity of the examined building, which included a hydraulic radiator-based heating system. The main limiting factors to the discharging rate were the slow temperature increase within the thermal mass and the heat conduction into the deeper wall layers. Moreover, the influence of the ambient temperature to the storage performance of the thermal mass has been highlighted. The authors conclude that good DSM can be achieved with shorter overheating periods at cold weather conditions. In addition, a Swedish pilot study [15] investigated the storage potential of the thermal inertia of five multi-family residential buildings connected with a district heating (DH) system. Results showed that heavy-weight buildings, with a structural core of concrete, can tolerate large variations in heat deliveries while still maintaining an acceptable indoor climate. Thus, the control can be applied in many buildings in DH systems at a relatively low cost. The study also demonstrated that degree hours instead of a fixed time constant can be a more accurate metric to represent variations in indoor temperature caused by the utilization of the thermal mass of the buildings. Although many examples of the simulated uses of thermal mass for storage have been reviewed on a building scale, there is a lack of cases calculating the potential of thermal mass for storage on a system scale.

A few papers dealt with the analysis of the thermal mass for storage potential on a system scale. Authors in Ref. [16] have presented a framework for planning cost effective operation of HVAC systems utilizing multi-building thermal mass. They have used a business-economic optimization approach and optimized thermal mass for storage of commercial buildings [16]. However, in their approach, thermal mass for storage was used to impact only the power sector while their time frame was one day. A simulation platform and different control strategies for utilizing the thermal mass for storage has been presented in Ref. [17]. The authors have

concluded that single buildings only have marginal influence on the energy system flexibility and that extension of the models to the entire city is needed [17]. They have also assessed the potential of utilizing the thermal mass for storage to increase the flexibility of the power sector. A detailed dynamic and grey box model has been developed in Ref. [18]. They have shown that between 3% and 14% of the load can be shifted by utilizing the thermal mass for storage [18]. However, they have also considered the impact of flexibility solely on the power sector and not on the district heating sector [18]. Furthermore, the buildings they have modelled were well insulated and no behaviour of older buildings has been presented. The primary energy supply in the power sector was dominated by gas (40%), followed by nuclear (35%), waste and renewables (10%) and hydro (9%) [18].

To continue on the latter, one paper has proposed a resistance-capacitance representation of building thermodynamics in order to incorporate thermal mass for storage into an integrated planning model [19]. They have used it for an Irish case study and their focus was on partially decoupling of heat and electricity demand, without including district heating systems into the model [19]. The authors concluded that by utilizing building thermal inertia, electrified residential heat costs can be reduced to the cost of benchmark technology, which were gas boilers in the Irish case [19]. The energy supply in the power sector was dominated by wind (40%), coal, peat, gas, oil and hydro. Other authors used Balmorel model with the thermal building model add-on in order to represent thermal mass for storage [20]. The model has not taken transient behaviour of heat transfer into account, while the average annual building energy consumption was taken from the literature without detailed modelling [20]. They have concluded that by utilizing thermal mass for storage, peak load could be shaved and that heat pumps operation could be prioritized for hours with low marginal generation costs [20].

So far, most of the research papers dealt with detailed calculations of thermal mass for storage on a building scale for specific building archetypes. The majority of the papers that modelled thermal inertia on a system scale have not captured dynamics of the heat transfer and transient behaviour well enough during the hours after the DSM event using reduced-order models. Moreover, almost no literature has been found, which focuses on the impact of utilizing thermal mass for storage on district heating supply in general; the presented papers have rather focused on the potential benefits that the thermal mass for storage could have on the power sector. Thus, the aim of this paper is to analyse building performance of different archetypes during the DSM events and to analyse the impact of DSM events on district heating systems. Moreover, the main objectives of the paper is to give an overview of the energy flexibility potential that an urban residential building stock can give to the energy grid and to project this potential into the future. In order to have a sufficiently detailed model, a two level modelling approach is proposed. First, detailed simulation of existing building archetypes shall be carried out in order to estimate their thermal autonomy or heat flexibility potential, obtain detailed heat demand pattern after the DSM events and possible additional peaks in heat demand of different building archetypes. Second, simulation output data shall be used as input for linear optimization model that optimizes the whole energy system and analyses the potential of thermal mass for storage on a system scale. In this way, the realistic building energy performance is captured in great detail while the analysis of the impact of DSM events on the energy system on a district scale brings clarity about the total potential of smart control in district heating systems.

The outline of the paper is structured as follows: the building simulation and system optimization models are described in the Methods section. The city of Sønderborg was chosen for the case

study and specifics of its energy system and the representative buildings are described in the Case study section. The potential of the thermal mass for storage is presented in the Results section. The results are put into perspective and compared with the findings from the other studies in the Discussion. Finally, the main points are summarized in the Conclusions section.

2. Methods

The following section presents the methods that were applied to model the investigated building stock, calculate the indicators and conduct the energy system optimization analysis. First, a detailed building energy model is presented. Second, the system indicators for evaluation of thermal mass for storage are introduced and different building heating scenarios presented. Third, an energy system optimization model is described. The energy system optimization model used the output of building simulations in terms of thermal autonomy, a difference in energy consumption compared to the reference case and the distribution of preheating and after cut-off heating demand as an input for running the optimization. Different steps used in the model are presented in Fig. 1.

2.1. Building energy modelling

The current analysis was conducted by use of building models. The building model and energy simulations were run in IDA ICE Version 4.7 [21]. The model behind the simulation tool is a detailed physical representation of the transient heat transfer phenomena taking place in a building. The model describing the external walls is a finite differences model of a multi-layer component. The buildings were simulated as single-zone models. The models were run with the Danish Design Reference Year (DRY) weather file [22]. These weather conditions are characterized by very cold winter temperatures. The monthly degree-days for the given climate and the annual outdoor temperature distribution according to [23] are presented in Appendix B. Based on literature, the utilization of thermal mass during times of very low ambient temperatures can have a good potential for DSM strategies. A cold and grey winter day was selected out of the DRY file to run the following experiment, during which the solar gains were very low and the average ambient temperature was -3°C . Thus, the heat losses were increased for the specific examined case. The global radiation for an exemplary week in January is presented in Appendix B. However, the ambient temperature on the selected day did not fall below -12°C , which is the dimensioning temperature for heating systems in Denmark. Deterministic occupancy profiles were modelled representing typical house living schedules, where there was no occupancy during 8am–3pm on weekdays. The heat supply system was DH and the heat emission system were hydronic radiators. No mechanical cooling or ventilation was assumed being installed in the buildings. The infiltration rate was determined based on wind-driven air flow. Internal walls and furniture mass were modelled taking into account the floor area that they covered, their material, thickness and the convective heat transfer coefficient.

The segmentation and characterization of the building stock was done according to [24]. Six building archetypes were created to represent different types of buildings according to their construction age and energy refurbishment level. These can be seen in Table 2. The properties of the building envelope and systems were created according to the TABULA [25], EPISCOPE project [26] and national building regulations. The building models were calibrated according to [27] based on measured hourly energy data acquired from 54 households in the city of Sønderborg.

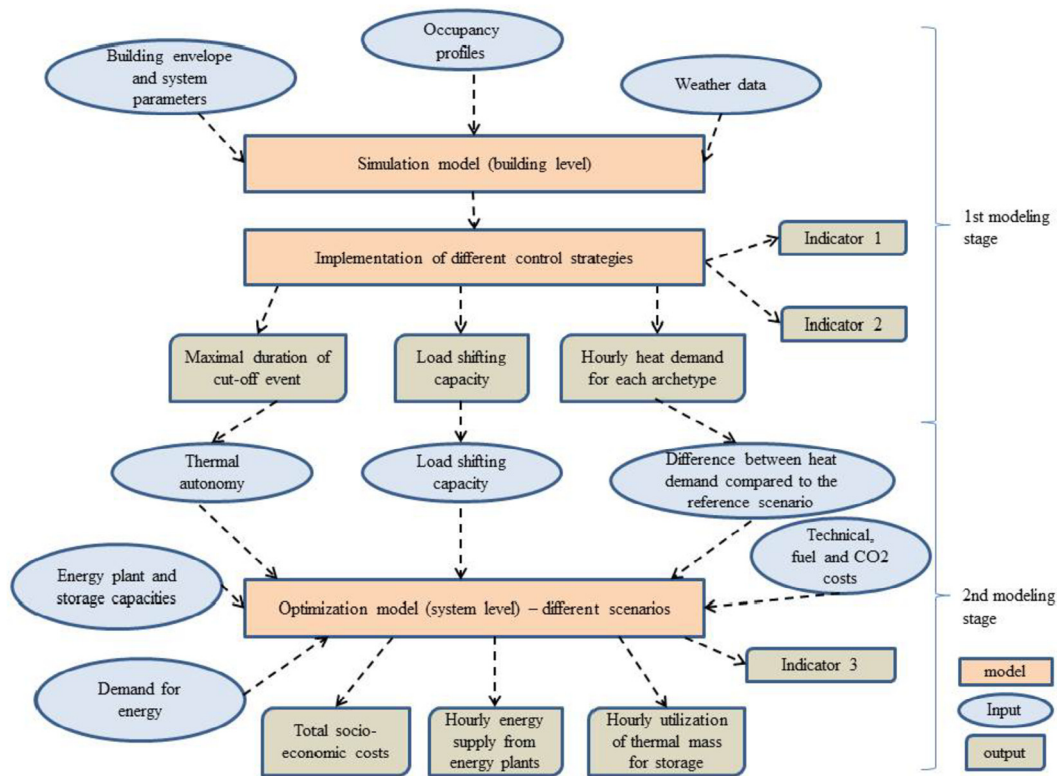


Fig. 1. The flow diagram of the two-stage modelling process.

2.2. Definition of thermal autonomy and adopted indicators

The thermal autonomy of the building was defined as an indicator of heat flexibility standing for the duration of the thermal comfort period [28], during which the operative temperature inside the building does not fall below 18 °C (1). This threshold was selected according to the Danish standard [29] corresponding to the third acceptable thermal comfort category, to reflect the degradation of indoor comfort in a straight-forward way. The thermal autonomy [h] was calculated on the basis of a heat supply cut-off experiment in the building models and was defined as the first indicator in our study.

$$Ind_1 = \min\{t|T(t) = 18^{\circ}\text{C}\} \quad (1)$$

The second indicator was defined as the difference in space heating demand of the building caused by the heating strategy implemented as opposed to the 'reference' heating demand (2). It was calculated on the basis of the thermal autonomy potential of each house. Indicator 2 [%] was calculated on the 24-h time period, starting from the hour 432 in the modelled year.

$$Ind_2 = \frac{Q - Q_{ref}}{Q_{ref}} \quad (2)$$

The exact time period was chosen as in none of the cases, the DSM event resulted in heat demand differences of more than 2% after the 24-h period.

2.3. Overview of different strategies of DSM events

To be able to determine the potential for thermal autonomy for all houses, heating control strategies were implemented. First,

three different scenarios were created, which can be seen in Table 1. The first scenario included a complete cut-off of the heating system with no preheating or overheating strategy for a period that equals the thermal autonomy of each house, according to equation (1), so that operative temperature would not decrease below 18 °C. In order to make our results more robust, this strategy was implemented on the afore-mentioned cold weather conditions, so that an unfavourable case is represented. The heating set point of the reference operation of the heating system was set to 21 °C in all scenarios based on the findings from calibrating the building models.

Then, the effect of preheating on the utilization of the thermal mass was investigated. The second scenario considered 2 h of preheating the houses up to 24 °C, followed by a complete cut-off of the heat supply on the same cold day as the first scenario, during the same time. The duration of the cut-off was found such that it equalled the result of indicator 1 after the preheating was applied, so that the temperature would not decrease below 18 °C. According to the third scenario, 4 h of preheating strategy up to 24 °C was applied, followed by a heating cut-off on the same day, as previously explained. The duration of the heat cut-off was again adjusted so that it matched the new autonomy potential after the 4 h of preheating. The three different strategies were implemented in the IDA ICE models through the option of variable controller heating set

Table 1
DSM scenarios implemented to the models.

Scenario	Action	Preheating [h]	Notation
1	Heat cut-off	0	CO
2	Heat cut-off	2	CO_2hPH
3	Heat cut-off	4	CO_4hPH

points ranging from 21 °C in the reference case to 24 °C in the preheating phase and to 18 °C during the heat cut-off phase, which were continuous throughout the entire simulation year.

2.4. Energy system optimization

A linear continuous optimization model was used in order to represent an energy system. The optimization was run using Matlab interface and Gurobi solver, one of the solvers with the fastest computation times for solving linear optimization problems [30]. After the building simulations had been run, inputs from the building simulations such as autonomy time, the maximum capacity of avoided energy consumption during a cut-off event for each archetype, increased demand before and after the cut-off event and their corresponding distributions were incorporated in the optimization model. The simulated day from the first modelling stage was used as a pattern for all the cut-off events during the heating season (1st October to 30th April). A sensitivity analysis for the latter assumption was carried out and commented on in the Discussion section. Between 1st May and 30th September load shifting utilization was not allowed in the model as the space heating demand during that period was low. The optimization model includes the power, heat, gas and transport sectors. The optimization model used was developed, presented and validated in Ref. [31]. As a short overview, the model optimizes the energy system with an objective function set to minimize the total socio-economic costs of the energy system (3). It optimizes the whole energy system during one year on hourly resolution.

$$\begin{aligned} \min Z = & \sum_{i=1}^n (fix_O\&M_i + lev_{inv\ i})x_i + \sum_{j=1}^m \left(var_O\&M_j + \frac{fuel_j}{\eta_j} \right. \\ & \left. + CO2_j \cdot CO2_{inten} \right)x_j + \sum_{k=1}^p (el_imp_exp_k + gas_imp_exp_k \\ & + dies_imp_k + petr_imp_k)x_k \end{aligned} \quad (3)$$

Energy plants were modelled using a black-box approach. The total socio-economic costs of the system incorporated levelized investment costs over the lifetime of the energy plants, fixed and variable operating and maintenance costs, fuel costs and costs of CO₂ emissions. Other taxes were not included. A discussion about the reasons for including the cost of CO₂ emissions and excluding the cost of other taxes in the total socio-economic costs can be found in Ref. [32]. The main reasoning for the latter is that the CO₂ emissions cost represents the internalized negative externality in terms of climate change costs imposed to the society. A detailed explanation of all the terms used in (3), as well as corresponding units, can be found in the Nomenclature, located at the end of this paper. As the goal of the optimization is to minimize the total socio-economic costs, different storage solutions will only be utilized if the corresponding load shifting can bring savings in the overall energy system costs. Based on the decision of the modeller, the model can optimize investments, too.

Furthermore, the model included all the district heating energy plants supplying the district heating network of the city, electricity plants (wind and PVs) erected as a part of the energy transition plan of the city and transportation demand for fuels. Electricity could be exported/imported over the system boundary (constrained by the transmission capacity), as well as fossil fuels for meeting the transport demand. Large (sensible) heat storage is another flexibility option that existed within the system boundary. Finally, gas CHP plant did not have a constraint on the minimum load level, which made it available to behave as a flexible generation

technology. The building thermal mass for storage, which is the focus of this paper, was the last source of flexibility in the local energy system.

Congestion of the district heating grid and electricity grids was not modelled. Moreover, the model does not include dynamic modelling of the district heating grid due to the complexity of the size of the current model.

For this paper, the model was significantly expanded in order to include the potential of thermal mass for storage of different building archetypes. For each modelled building archetype, a set of variables for cut-off event, increased after cut-off heating demand and increased preheating were introduced. In order to meet the increased heat demand after the cut-off event, as well as before the cut-off event when the heating strategy included preheating, inequality constraints (4) and (5) were introduced.

$$\begin{aligned} cutoff_{t,x} \cdot C_{x,y} &\leq preheating_{t,x,y} \\ \forall t \in \{1, \dots, 8760\}, \forall x \in \{1, \dots, X\}, \forall y \in \{1, \dots, Y\} \end{aligned} \quad (4)$$

Where $cutoff_{t,x}$ represents the avoided heat demand due to the cut-off event [MWh] for each building archetype x in every hour t of the year. $C_{x,y}$ represents coefficients of hourly difference in district heat demand in each preheating hour y (compared to the reference heating demand pattern), obtained as a part of calculation for indicator 2 of the first step of the model. Finally, $preheating_{t,x,y}$ represents the increased heat demand [MWh] prior to the anticipated DSM event.

$$\begin{aligned} cutoff_{t,x} \cdot C_{x,z} &\leq afterheating_{t,x,z} \\ \forall t \in \{1, \dots, 8760\}, \forall x \in \{1, \dots, X\}, \forall z \in \{1, \dots, Z\} \end{aligned} \quad (5)$$

Where $afterheating_{t,x,z}$ represents increased heat demand after the cut-off event [MWh] in each after cut-off heating demand hour z .

The $C_{x,z}$ and $C_{x,y}$ coefficients were used to realistically capture the dynamics of the heating demand in hours before and after the cut-off events took place.

The sum of preheating hours y , the duration of cut-off event (equal to the value of Indicator 1) and after cut-off heating demand hours z were set to 24 h in order to match the indicator 2 from the first part of the model (6).

$$y + Ind_1 + z = 24 \quad (6)$$

In order to further integrate the first and the second part of the model, only one *maximum capacity* cut-off event was allowed in any 24-h period (7). The latter constraint was introduced in order to acknowledge the calculation method used for the estimation of indicator 2. However, the system could choose to have more than one cut-off event during any 24-h period, as long as the sum of the avoided heat demands during all the cut-off events did not exceed the maximum capacity of a single cut-off event.

$$cutoff_{t,x} + cutoff_{(t+1),x} + \dots + cutoff_{(t+23),x} \leq cutoff_{max,x} \quad (7)$$

Where $cutoff_{max,x}$ represents maximum avoided heat demand during the cut-off event for each building archetype x , calculated in the first part of the model. Inequality constraint (7) allows more than one cut-off event during the 24-h period as long as the sum of them does not exceed maximum possible cut-off demand.

Finally, after the optimization part of the model had been run, the economic indicator (Indicator 3) was calculated (8).

$$Ind_3 = \frac{C_{operational,ref} - C_{operational}}{C_{operational,ref}} \quad (8)$$

Indicator 3 represents the difference in the operational costs of the district heating system, without the costs of the other parts of the energy system. Operational costs of the district heating system did not include investment costs of the energy plants. They were calculated using the equation (3) for the plants operating in the district heating network, without including the first and the third summation terms. The economic indicator encompassed operational costs of the district heating system only, as the district heating sector was the focus of research carried out in this paper. For the purpose of calculating the operational costs of DH systems, the income from cogeneration units selling electricity to the grid was included as revenue in the operational costs of the district heating systems, reducing the overall operational costs of the district heating system, while in the same time all the fuel costs of running the cogeneration units were included as expenditure.

3. Case study

The city of Sønderborg was chosen as the current case study. It is located in the south of Denmark with a population of 27,500 inhabitants as reported in 2011. It includes several types of energy supply plants and the whole municipality has started a transition towards net zero carbon until 2029. The highest share of heating demand is attributed to residential demand, accounting for 69% of the total heating demand (Fig. 2). In Denmark, housing accounts for 64% of the total heat demand. As Sønderborg can be considered representative in terms of heat demand, and ambitious in terms of integrating variable renewable energy sources, it was decided to focus on the residential building stock of Sønderborg to investigate the potential for energy flexibility provided by the thermal mass included in the building envelope and internal walls. Around 53% of the area's heat demand is covered by the local district heating network [33].

3.1. Characterization of Sønderborg' building stock

The focus of the current study is on single-family houses (SFH), which represent the largest share of residential buildings in this area. The building stock of Sønderborg was represented by archetypes as afore-mentioned. The categorization follows the general guidelines of the TABULA database. According to the TABULA project, in general there are ten typical Danish building archetypes corresponding to SFH [25]. One archetype belongs to each of the ten proposed age bands, which reflect a shift in building tradition and the introduction of building energy codes. The same age bands were used in our case to extrapolate the results of simulated building archetypes to the system level. Based on the available energy data that we had and used to calibrate the building models,

six building archetypes were created representing the majority of the SFH in Sønderborg. The models of the archetypes are presented in Table 2. The construction age of all the building models, their gross floor areas along with the average heat loss coefficient (U-value) of the total building envelope and internal heat capacities are presented. The time constant of the buildings is also presented in Table 2. It is calculated as the ratio of the total heat capacity of the building and the total heat loss coefficient including transmission, ventilation and infiltration losses. The time constant gives an indication of the response pace of the building to different stimulations such as change in heating or outdoor temperature, hence being very relevant to the current study. It is evident that newer buildings have longer time constants. The total energy use intensity and peak energy demand over a full simulated year, which are also presented in Table 2, give an indication of the energy efficiency of the investigated building stock. The energy demand results were calculated after the models were calibrated according to the measured energy data and with the system properties and internal conditions that were described for the reference case. There are two archetypes corresponding to SFH built in the 1960's, since one of the two (1960's ref.) had undergone more extensive energy refurbishments based on the calibration findings. The U-values give an indication of the insulation state of the building envelope relating to how airtight each building is. The lower the U-value, the more airtight the building is and fewer thermal bridges it has. The refurbishment implemented in each building model/archetype -also affecting the heat loss coefficient of the building envelope- was decided based on the results of the calibration with measured energy data as mentioned earlier. The majority of the houses were made of heavy-weight insulated brick walls with an average thickness of 340 mm. The internal walls in the majority of the investigated houses consisted of aerated concrete of 75 mm thickness and were designed based on typical floor plans of Danish SFH. The idea of using archetypes to characterize the building stock is that one archetype represents a building category having uniform characteristics in terms of building construction and systems that are regulated by building codes. Thus, the energy performance of buildings belonging in the same category will be quite similar making one archetype representing each category sufficient. More information about this approach can be found in Ref. [24]. The six building archetypes that were created represented 60% of the residential building stock and 55% of the district heating demand in Sønderborg. Most of the building stock not represented in Table 2 (26.4% of the building stock and 36.9% of district heating demand), were buildings built before 1930. The latter building stock has similar characteristics to the first archetype in terms of energy use intensity, dominated by low time constants.

3.2. Overview of Sønderborg district heating system

In 2015, the total district heat supplied to the customers in the city was 288.95 GWh (not including 23% of distribution losses), based on information provided by the Sønderborg Fjernvarme, which is the operator of the district heating system. The Sønderborg DH operation data, such as volume flows, supply and return temperatures, as well as the circulation pumps electricity demand, can be found in great detail in Appendix B. According to the energy transition plan towards 2029, an increased share of households connected to the district heating systems has been anticipated [33]. The current district heating plants that supply the city of Sønderborg with heat are listed in Table 3.

All household owners in Denmark are obliged to report certain information about their real estate, including the year of construction and last refurbishment of the building, energy consumption, heat energy source, type of the heating system, etc. in

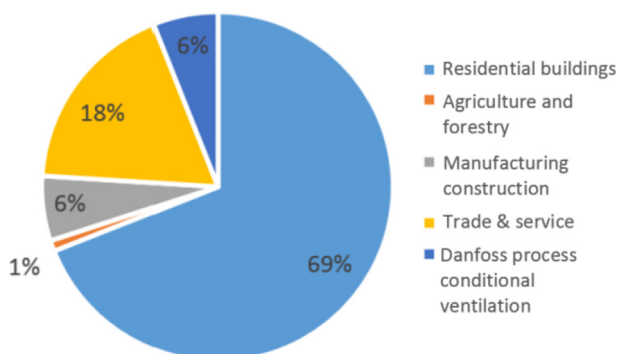








Fig. 2. Allocation of heat demand on the building categories in Sønderborg 2007 [29].

Table 2
Building archetypes representing the examined Danish residential building stock.

Building archetype	Construction age	Floor area [m ²]	Average U-value of total building envelope [W/m ² K]	Internal heat capacity e+07 [J/K]	Time constant [h]	Energy use intensity [kWh/(m ² year)]	Peak demand [kW]	Share of buildings represented [m ² /m ²] [%]
	1930's	85	0.72	1.44	20	225.7	7.5	5.9
	1950's	87	0.47	2.34	43	148	4.4	6.8
	1960's	140	0.54	2.33	29	143.6	7.3	7.8
	1960's ref.	119	0.43	2.13	39	111.6	5.1	11.8
	1970's	136	0.51	3.69	51	132.6	6.8	10.3
	1990's	137	0.31	5.87	134	84.5	3.8	17.5

*Pictures taken from Refs. [34–36].

Table 3
The current district heat supply plants [31].

Energy plant type	Electrical power [MW _e]	Heat generation capacity [MW _{th}]
Waste CHP	4.5	20
Gas CHP	40	53
Gas boilers		100
Solar heating (centralized)		5.2
Bio-oil		5.4
Geothermal + biomass driven absorption heat pump		12.5

the so called BBR Database [37]. For the purpose of this paper, we have obtained the BBR data for the city of Sønderborg through the ProjectZero company, the managing company of the net zero carbon energy transition of Sønderborg. Data has been cleansed removing unreasonable values. The high uncertainty in some of these variables used as inputs to the building models has been balanced by the calibration process as earlier mentioned, according to which measured energy data were used to calibrate the inputs of the building models so that the predicted and actual energy demand match.

The energy system of Sønderborg should undergo significant changes until the year 2029 and different renewable energy plants are anticipated [33,38]. The whole municipality of Sønderborg will try to achieve carbon neutrality by 2029. Important contribution towards this goal should be made by the district heating sector. Thus, in order to assess the effects of the potential utilization of the thermal mass for storage in the future energy system, an additional scenario (the 4th one, designated CO₂hPH_2029) was modelled. An overview of the plants, which should be installed until the year 2029 can be seen in Table 4. Only zero-carbon energy technologies are anticipated for the year 2029. Furthermore, it was complicated to extract the capacity of solar thermal anticipated in the DH network of the City of Sønderborg, as the transition plans are made for the whole municipality of Sønderborg. In order to cope with the latter, it was assumed that the maximum solar thermal generation would correspond to the 15% of the yearly DH demand in 2029. Effective solar thermal generation supplied to the district heating could be lower if there would not be enough demand during the peak generation hours and there would be a lack of heat storage capacity in the system.

It should be noted from Table 4 that the capacity of biomass boilers in the year 2029 was not fixed before the optimization was run. Opposite to the current portfolio of the DH supply plants, the future investments in the plants can be projected taking into account different technologies or flexibility options, such as utilizing the thermal mass for storage. In order to account for the potential savings of the capital costs, by reducing the installed capacity in the DH system, biomass boilers as a peak technology was also

Table 4
Energy plants capacities anticipated in 2029.

	Installed capacity 2015 (MW _{th})	Installed capacity 2029 (MW _{th})
Gas boilers	100	0
Gas CHP	53	0
Waste CHP	20	20
Geothermal + biomass driven absorption heat pump	12.5	12.5
Biomass boilers (including bio-oil)	5.4	^a
Large scale heat pumps	0	12 (heating capacity)
Solar heating	5.2	40
Heat storage	4000 MWh	4000 MWh
Wind turbines	14.6	180
Photovoltaics	14.8	60

^a Optimized by the model (a minimum capacity needed to satisfy the heating demand in all hours throughout the year).

Table 5
Average wholesale electricity prices (based on Nordpool el-spot [41]) and CO₂ emission prices used in the scenarios.

	2015	2029 ^a
Average electricity price (€/MWh)	22.89 [41]	59.64 and [42]
CO ₂ emission price (€/t)	7.6 [42]	13.6 [42]

^a Real future prices, i.e. the future prices were adjusted for inflation (2016 prices).

optimized in the CO₂hPH_2029 scenario. Thus, the resulting capacity of biomass boilers was the minimum capacity still being able to satisfy the DH demand in all hours during the year.

Furthermore, it is expected that the increased share of households will connect to the district heating grid. The DH demand should increase by 13% compared to the 2015 share, taking into account significant energy savings, which are anticipated in the building sector [33]. Furthermore, energy retrofit of buildings will increase the share of the buildings with longer thermal autonomy, i.e. more buildings will have better air-sealed and thermally insulated envelope. Historically, the energy retrofit rate of the buildings in Denmark has been 1% per year [39,40]. We adopted the same rate until the year 2029. Moreover, we assumed that the retrofitted buildings behave in the same way as the 1990's archetype, as those were the newest modelled buildings. Finally, for the 2029 scenario, the second strategy (with two hours of the preheating time) was used. The latter also means that the indicators 1 and 2 are equal in CO₂hPH and CO₂hPH_2029 scenarios. CO₂ emission costs, as well as the average electricity prices can be seen in Table 5.

One should also note that the assumed volatility of the prices was greater in the year 2029, as more intermittent renewable energy sources was assumed to be installed in the power grid. The spread between the highest and the lowest electricity price was 192.3 EUR/MWh in 2015, while the assumed spread was 302.6 €/MWh in 2029.

4. Results

4.1. Results of the building energy modelling

As mentioned in the Methodology, one representative winter day had to be identified and selected as the date when the experiments in the simulation part of the model would be carried out. These results were then reproduced according to the optimization results within the heating season of a year in the second stage of the model, making the system level results of the optimization part of the model robust. So, the heat cut-off was applied on January 19, which was found to be one average cold day of the reference year with the mean daily ambient temperature being -3 °C and very low solar gains in order to isolate their effect on heat flexibility.

Table 6
Results of indicator 1 (thermal autonomy) and 2 (difference in heating demand) 2.

Archetype	SCENARIO 1 (CO)		SCENARIO 2 (CO_2hPH)		SCENARIO 3 (CO_4hPH)	
	Ind ₁ [h]	Ind ₂ [%]	Ind ₁ [h]	Ind ₂ [%]	Ind ₁ [h]	Ind ₂ [%]
1930's	1	−0.3%	1	1.3%	2	4.2%
1950's	2	−1.9%	3	−1.5%	4	−0.7%
1960's	1	−1%	2	−2.1%	2	−1.4%
1960's ref.	2	−1.5%	3	−2.0%	4	−1.5%
1970's	1	−0.3%	2	−1.2%	2	0.4%
1990's	5	−14.6%	6	−18.1%	6	−15.2%

The effect of the preheating strategies on the energy use for heating can be seen in Table 6. These results should be interpreted with regard to the information presented in Table 2. The buildings with the lowest average U-values have the highest thermal autonomy potential (Ind₁), indicating that the effect of heat losses in the examined buildings is dominating. It should be also noted that even though the 1970's archetype has a longer time constant than the 1960's refurbished archetype, its better insulated envelope (thus lower U-value) results in a longer thermal autonomy potential. This validates the previous finding that heat losses have a more significant effect than the heat capacity of the building or its thermal mass for the specific investigated buildings under the cold and grey weather conditions. It should be noted that the internal wall mass for all archetypes was modelled in a very similar way, having similar construction characteristics (materials and wall thickness), as well as the share of the volume of internal walls to the floor area was assumed to be almost the same for all the different models. It is also evident that as the duration of preheating increases, the results of thermal autonomy (Ind₁) increase in most archetypes. The effect of preheating is not pronounced on the newest archetype, which represents SFH built in the 1990's. This is attributed mainly to the fact that the building has airtight envelope leading to low heat losses, so its thermal autonomy potential is already high (6 h) and is slightly improved by preheating, which is not evident due to rounding. According to [28], the effect of transmission losses exceeds the effect of thermal mass when it comes to thermal autonomy potential of a building and the peak load that is created after overheating strategies. Since the weather conditions on the day of the experiment were cold, the effect of the transmission losses on the specific indicators is outlined. Therefore, it is confirmed that buildings with airtight building envelopes and very low overall heat transfer coefficients would perform better in general with regards to heating demand. Looking at indicator 2, we observe that the cut-off of heating led to savings in space heating demand in all archetypes compared to the reference case when heating was always on, as expected. The heat losses were decreased due to the lower average internal temperature during the day of the cut-off. The highest decrease was observed for the newest archetype, which allowed the longest duration of cut-off. Indicator 2 could be positive or negative for the two preheating scenarios, as the duration of the preheating and of the subsequent cut-off may or may not lead to savings of space heating energy use. In the majority of the houses, even in the case of four hours of preheating up to 24 °C, the heating demand was still lower than the reference case except for the 1930's archetype and the 1970's archetype. Thus, it can be concluded that longer preheating times do not have the same effect in all buildings.

Operative temperatures and heat consumption of the 1990's archetype and the 1960's archetype during the 24-h period around the simulated cut-off event can be seen in Fig. 3 and Fig. 4, respectively. The latter represents the archetype with short time constant and a low thermal autonomy (1–2 h in different

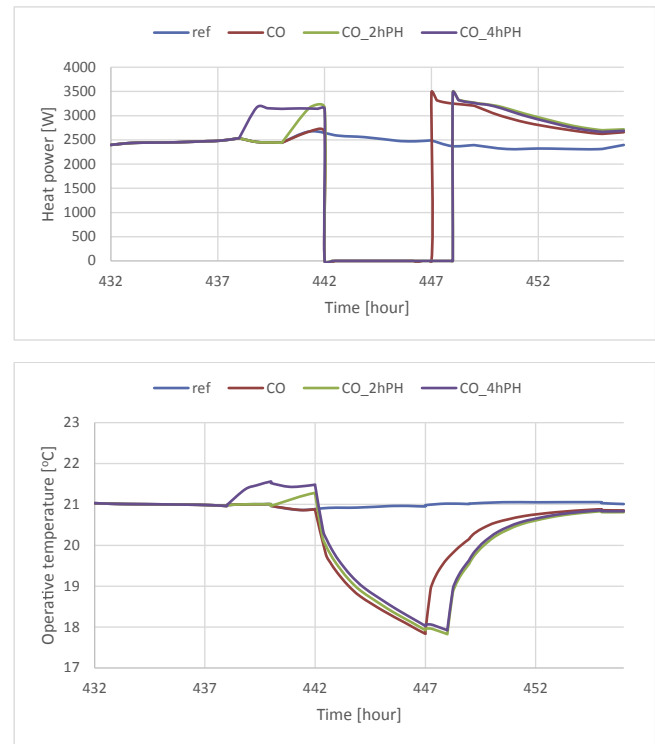


Fig. 3. Operative temperatures (up) and heat demand (down) of the 1990's archetype in different scenarios.

scenarios), while the former presents the archetype with the longest time constant and longer thermal autonomy (5–6 h). For the implemented DSM strategies, we can see that operative temperature inside the 1990's and 1960's archetypes varies between 18 °C and 22 °C. Furthermore, the preheating scenarios CO_2hPH and CO_4hPH lead to higher initial internal temperatures for both archetypes. The thermal comfort remains to be acceptable in all cases according to [29]. When comparing the reference case and the cases with the occurring DSM events, one can note new peaks in heat demand. These peaks occur both during preheating and after heat cut-off phase. We can observe that the effect of preheating strategies is minimized on the archetype of 1990's leading to similar thermal autonomy results. The magnitude of the peak load that is created after the cut-off is similar for all three scenarios and it is defined by the capacity of the heating system. For the same archetype, even though the preheating set point is set to 24 °C, this cannot be achieved within the given time, with the maximum operative temperature inside the house being 21.8 °C for the CO_4hPH scenario. Despite the 4-h preheating, the thermal autonomy is not much prolonged as mentioned earlier due to the long-time constant and the low heat loss coefficient of the building envelope of the 1990's archetype. We can see that the operative temperature stabilizes in the three scenarios at the end of the day reaching almost the same value of the reference case where no cut-off was applied. Looking at the heat power graph of Fig. 3, it can be observed that the peak load that is created after the heat cut-off is almost equal for the three scenarios, independent of the preheating strategy as already mentioned. Similarly, 1960's archetype has a slightly increased thermal autonomy after preheating scenarios CO_2hPH and CO_4hPH as seen in Fig. 4. The magnitude of the peak load seems again to be independent of the preheating strategy and is very much defined by the maximum capacity of the heating system that is almost fully utilized in these cases of a sudden internal temperature drop. It should be noted that the heating system

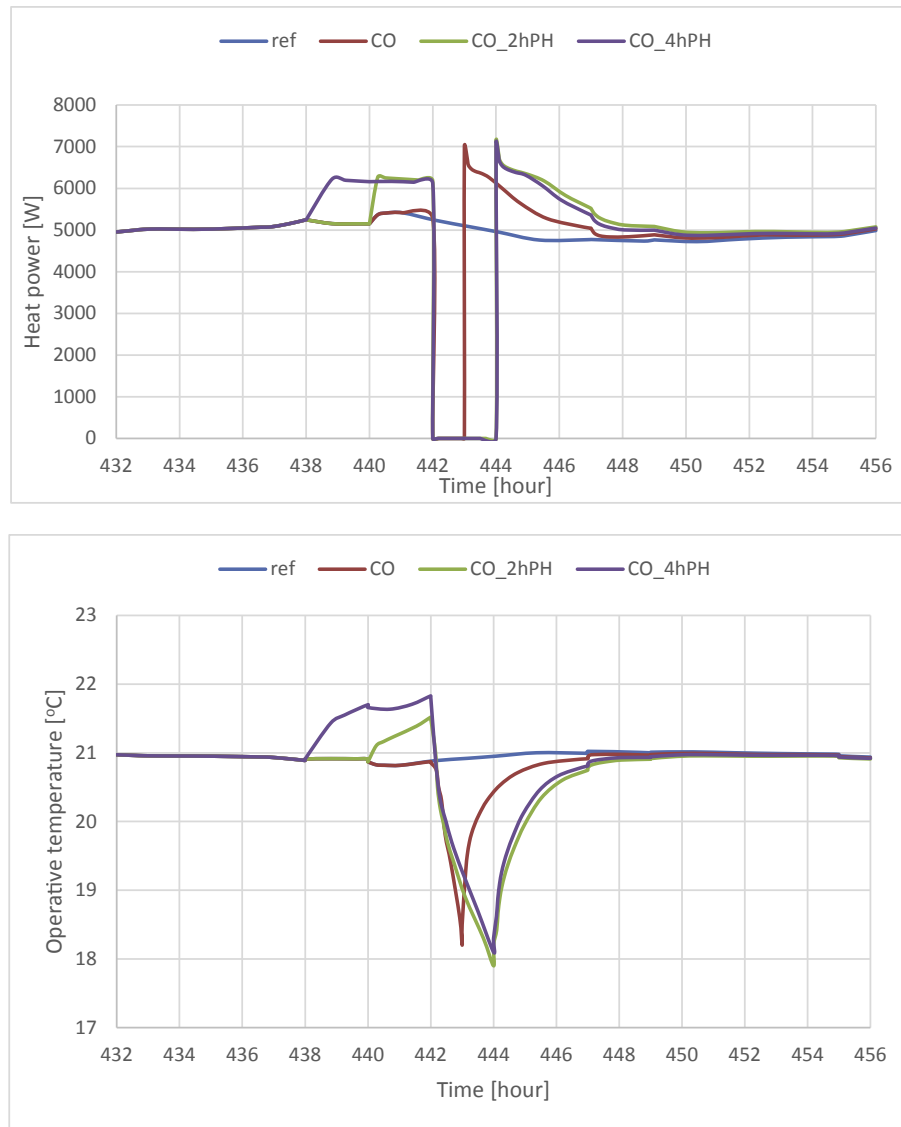


Fig. 4. Operative temperatures (up) and heat demand (down) of the 1960's archetype in different scenarios.

is dimensioned in the construction phase of the building. So, when the building undergoes energy refurbishments, the heat demand may be reduced but the capacity of the heating system remains the same as before. That is the reason that the older archetype has higher peak loads after the cut-off compared to the newer archetype. The operative temperature of the 1960's archetype in the CO scenario does not seem to reach 18 °C due to the setup of the controller that was set to take average values of very short time steps to eliminate temperature changes within a few minutes.

4.2. Results of the energy system optimization

The total shifted heat demand during the year, in terms of avoided heat demand during the cut-off events, for the 3 different strategies for the year 2015 and strategy two for the year 2029 (scenario CO_2hPH_2029) can be seen in Fig. 5.

In all the scenarios, the newer archetypes contributed more to the overall load shifting than the older ones. The oldest houses, represented by the 1930's archetype were utilized only in the CO scenario. All other archetypes contributed to the load shifting in all

the scenarios. Archetypes 1960's ref, 1970's and 1980's accounted for 65%–70% of the total shifted load, in the first three scenarios. Moreover, the relatively old building archetype 1950's was often utilized, especially in scenarios CO_2hPH and CO_4hPH when it had larger autonomy (3 and 4 h compared to the 2 h in the CO scenario). It was found feasible to utilize almost all of the identified load shifting potential. The maximum possible capacity of the load shifting was 5.6%–8.4% of the total DH demand of the city of Sønderborg in different scenarios. The real activation of the thermal mass for storage in different scenarios showed that the shifted load accounted for 5.5%–7.7% of the total DH demand in the different scenarios.

Differences in operational costs of the district heating system, represented by Indicator 3, can be seen in Table 7.

The largest saving potential occurred in the 2029 scenario. The energy system of the 2029 is anticipated to have more capital intensive, but efficient technologies, such as large scale heat pumps and centralized solar thermal systems (Table 4). The main reason for much larger operational savings in 2029 was the larger capacity of solar thermal technology that was less curtailed when utilizing

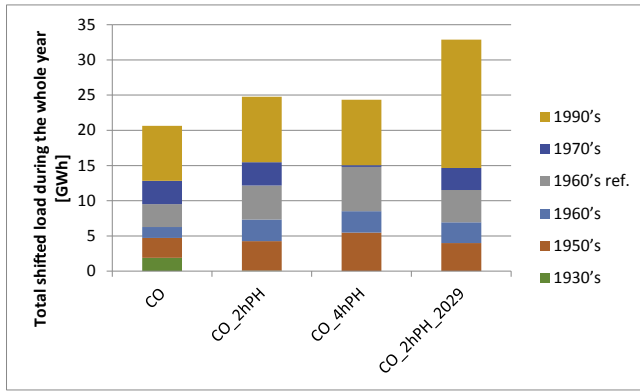


Fig. 5. The total amount of shifted heat demand on the system scale in different scenarios for one whole heating season.

the thermal mass for storage. Moreover, more refurbished buildings meant that the larger share of buildings behaved as the 1990's building archetype, having larger time constants and lower energy consumption (Indicator 2).

The resulting capacities of the peak biomass boilers for the year 2029 were 52.2 MW in the reference (2029) case and 37.7 MW in the CO_2hPH_2029 scenario. The latter means that taking into account the thermal mass for storage and corresponding reduction in heat demand (indicator 2) when planning future investments, reduced the needed peak capacity. The reduced peak boiler capacity of 14.5 MW represents 14.6% of the peak DH demand of the city of Sønderborg throughout the year. Although it was not the focus of our study, reduced capacity of the installed plants reduced the total capital costs of the whole energy system by 2% in 2029, equal to 770,000 EUR.

Comparing the CO_2hPH_2029 scenario and the reference scenario for the year 2029, the optimization results showed that large scale solar-thermal was more utilized. Gas boilers and large scale heat pumps had significantly lower heat generation. Although the capacity of solar thermal DH was larger in the year 2029 than in the 2015, the overall capacity of it was still relatively low. However, the results showed that it could be possible that in systems with larger shares of solar thermal DH, the utilization of thermal mass for storage would be even more attractive economically.

5. Discussion

One of the main goals of this paper was to focus on the impact of utilizing building thermal mass for storage on district heating supply and its operating expenses. Our analysis showed that operational savings can be much larger in the future, with larger capacities of the intermittent sources installed in the DH system, larger average electricity prices and higher electricity price fluctuations in the energy system. Load shifting in relative terms was mostly utilized in the CO scenario, during the 98% of the possible time. Although in the CO_2hPH_2029 load shifting possibility was utilized the most in the absolute numbers (Fig. 5), in relative terms its utilization was lower than in the CO scenario, i.e. it utilized 96% of the total thermal mass for storage capacity throughout the year. DSM events were usually triggered in mornings, in the duration of 2–3 h, and often in the evenings, especially during the winter time with higher overall DH demand. Heating savings related to the activation of thermal mass for storage were assessed using the indicator 2. Only two archetypes did not have heating savings in CO_2hPH, CO_4hPH and CO_2hPH_2029 scenarios. All other building archetypes had heating savings, resulting in a lower overall DH demand. One should note that the latter means that certain share of load shifting occurred due to the energy savings itself. In order to check the share of savings that comes from reduced average temperature when activating the thermal mass for storage, simple sensitivity analyses were carried out for CO_2hPH and CO_2hPH_2029 scenarios. To carry out the sensitivity analyses, the reference heat demand was reduced in order to be equal to the total yearly heat demand in the CO_2hPH and CO_2hPH_2029 scenarios. The sensitivity analyses showed that the operational economic savings in the CO_2hPH scenario reduced from 1.0% to 0.17%. In the CO_2hPH_2029 scenario, the operational economic savings reduced from 4.6% to 3.1%. However, one should note that the actual implementation of the proposed preheating scenarios and heat supply cut-off to the residential building stock requires a central management system, the same one that allows the activation of thermal mass for storage, which would impose a non-negligible capital cost to the system.

All scenarios showed that despite most of the energy plants reduced their generation (Table 8) solar DH increased its useful output in all the scenarios. The latter could be especially observed in the carbon neutral scenario carried out for the year 2029, when 3.8 GWh more solar thermal heat generation was effectively

Table 7

Comparison of the operational costs of district heating in the city of Sønderborg in different scenarios (indicator 3).

	Reference (2015) ^a	CO	CO_2hPH	CO_4hPH	Reference (2029) ^a	CO_2hPH_2029
Operating costs of DH system [10 ³ €]	5238	5201	5186	5164	5687	5425
Savings compared to the reference case [%] (Indicator 3)		0.7%	1.0%	1.4%		4.6%

^a Reference case costs were obtained by constraining the modelled system not to utilize the thermal mass for storage.

Table 8

Difference in generation of district heating plants in the city of Sønderborg compared to the reference case (the first three scenarios compared with the reference case for the year 2015, the last scenario compared with the reference case for the year 2029).

	CO [MWh]	CO_2hPH [MWh]	CO_4hPH [MWh]	CO_2hPH_2029 [MWh]
Solar heating	111	235	247	3762
Geothermal + biomass driven absorption heat pump	–1	–44	–52	–734
Biomass boilers	–45	–74	–68	–6755
Waste CHP (heat generation)	0	0	0	30
Gas CHP (heat generation)	98	–5	–36	0
Gas boilers	–1361	–1852	–1460	0
Heat pumps	0	0	0	169

*The full results of the generation of different energy plants in the reference cases can be seen in Appendix A.

utilized compared to the reference scenario for the year 2029. Moreover, the thermal autonomy was more important factor for triggering DSM events from the system point of view than the energy use intensity of different building archetypes.

There were four main flexibility sources in the modelled energy system: flexible generation of gas driven plants, import/export of electricity over the system boundaries, heat (pit thermal energy) storage and the building thermal mass for storage. In order to check the operation and mutual influence of pit thermal energy storage and the activation of the thermal mass for storage, another sensitivity analysis was carried out for the CO₂hPH₂₀₂₉ scenario. In the sensitivity analysis, except the biomass boilers capacity which was not constrained, the capacity of pit thermal energy storage was not constrained either. The analysis showed that the optimal capacity of pit thermal energy storage, that minimizes the total socio-economic costs of the energy system, was 158,000 m³, behaving as a seasonal storage. The significantly increased capacity of the thermal storage further reduced the need for additional 10 MW of biomass boilers due to the increased utilization of both solar thermal and the thermal mass for storage. The total load shifted by activating the thermal mass for storage in the sensitivity analysis was 34.1 GWh, compared to the 32.9 GWh in the CO₂hPH₂₀₂₉ scenario. The latter shows that the two storage flexibility options are mutually complementary. The thermal mass for storage behaved as intra-day storage, shaving daily peaks in demand, while the pit thermal energy storage behaved more as seasonal storage, shifting lots of excess solar thermal generation during the summer time to the winter time.

In the first three scenarios, the majority of savings came from less utilization of gas boilers. In the CO₂hPH₂₀₂₉ scenario, the majority of energy savings came from less utilization of biomass boilers. The latter also shows that implementation of thermal mass for storage could lead to savings in consumed biomass, allowing larger amounts of sustainable biomass to be utilized for the transition of the heavy-weight transport sector. It was shown that the transition of the heavy-weight part of the transport sector to the renewable one will be especially energy demanding [43].

Compared to the other studies that assessed the potential of thermal mass for storage and were presented in the literature review, our study simulated real existing buildings from our case study. The simulations were detailed, taking transient behaviour into account as opposed to steady-state or quasi-steady-state models. The latter has allowed us to capture the peaks in heat demand just before (when preheating was applied) and after the cut-off events, a finding that would be hard to obtain using less detailed models. Moreover, our study focused on the DH supply system in a holistic way; not just on its electrified part or on integration of intermittent electricity sources by utilizing the thermal mass for storage. On the other hand, because of the coupling of detailed simulation model with the holistic energy supply model, we had to use a two-level approach and not the integrated model. Furthermore, the DSM strategies were implemented on cold weather conditions with very low solar gains and mean daily temperature of -3 °C, which represented a cold and grey winter day, which is quite common in Danish heating season so that our system level results become more robust. Two other cases were also modelled to estimate the flexibility potential on a more favourable case and on a least favourable one with regards to the thermal autonomy potential of buildings. These were i) an equally cold but entirely sunny day, with an average ambient temperature of -3 °C and ii) an equally grey day but colder with an average ambient temperature of -6 °C. The experiment was run for the newest archetype representing SFH built in the 1990's and showed that the effect of solar gains is significant. In particular, for the clear day the thermal autonomy potential of the newest

archetype increased by 7 h in the cut-off and preheating scenarios due to the highly increased solar gains that coincided with the time of the cut-off. When a colder grey day was investigated, the thermal autonomy potential of the same archetype decreased by 2 h due to the increased thermal losses. Thus, the flexibility results are subject to significant changes based on the weather conditions. However, it should be noted that the extremely sunny day that was examined represents only 9% of the days in a typical Danish heating season (October–April), while the share of very cold days, when the average daily temperature falls below -3 °C, is 10%. In addition, the examined 1990's archetype in this sensitivity analysis was characterized by a very long time constant and low overall heat loss coefficient, thus benefiting significantly from high solar gains. These results would be different for the older houses. Therefore, it is assumed that our initial choice of day to run the experiments represents the building performance during a Danish heating season quite well. The effect of warmer days on heat savings [kWh] could be further investigated. Overall, it is expected that much warmer days would lead to lower heat savings due to decreased heating demand. Testing extremely cold ambient temperatures falling below -12 °C was beyond the scope of this analysis, as this is the dimensioning temperature of heating systems according to the Danish standards, below which the heating systems would not be able to operate sufficiently to achieve acceptable thermal comfort.

Out of other studies, one study showed that between 3% and 14% of the load can be shifted by utilizing the thermal mass for storage [18]. Our findings showed that the theoretical potential for load shifting is between 5.6% and 8.4% and the economic potential between 5.5% and 7.7%, according to the different scenarios. Thus, our results were similar with a smaller variation in different scenarios. A grey-box model applied for in Ref. [19] showed very low total system cost savings when utilizing the thermal mass for storage. However, if significant electrification of the heating sector would be pursued, thermal mass for storage would lead to more significant savings, up to 15% [19]. Although our results are not directly comparable, the total system costs in our case were also only marginally lower compared to the reference case. Finally, the linear optimization model developed in Ref. [20] showed that the thermal mass for storage was mostly utilized to shift the morning peaks and to a some extent the late afternoon peaks. The same behaviour occurred in our case, especially in the colder periods. They have further claimed that smart controls should be invested in approximately 34% of the buildings. Our findings showed that the system would economically benefit, in terms of operational costs of the district heating system, by equipping up to 98% of the modelled buildings with smart controls, which equals to 59% of the total housing stock in the city of Sønderborg. Only the buildings with very low autonomy time should not spend money on implementing smart controls. It is yet unclear what the price of implementing smart controls in district heating systems on this wide scale would be. However, based on the CO₂hPH scenario and assumed lifetime of smart controls of 15 years, the maximum investment in smart controls of 261 EUR per household would be economically feasible. Larger investments in smart controls would not be recuperated by operational savings in the district heating system.

Regarding the building energy simulations, IDA ICE uses a variable time step solver to capture the dynamics of the system. However, the cut-off duration was rounded up on hourly intervals to reduce the complexity of the optimization problem and thus, the computation time. If a simpler optimization problem was to be solved, the implemented cut-off times would be converted to 30-min intervals or less. Thus, the effect of preheating strategies on the heat flexibility potential of the archetypes would be more

evident since rounding would be avoided. In addition, it should be noted that despite the preheating set point of 24 °C, the operative temperature inside the buildings could not exceed 22 °C even in scenario 3 (CO_4hPH), which is due to the high inertia of the internal walls and mass, as well as the relatively short preheating duration. The lowest operative temperature of 18 °C was selected to determine the duration of the heating cut-off, so that acceptable thermal comfort was ensured according to ASHRAE and Danish standards and also provide some flexibility to the system. One can argue that this temperature might be too low when occupants would be present or too high if no occupancy is assumed during the cut-off times. Therefore, further investigations are proposed that will study a wider range of lowest temperature threshold and its effect on heat flexibility. Another proposal would be to introduce an additional indicator that will represent the deterioration in the thermal comfort from occupant's side. That would give the human perspective to the effect of DSM approaches. Moreover, some tests were run where internal wall mass was neglected from the building models which resulted in a much lower inertia of the building. Consequently, the thermal autonomy potential was decreased in the majority of archetypes since the total heat capacity decreased. Thus, internal walls proved to be decisive for the inertia of the building, which in combination with the U-value of the building envelope determine the heat flexibility indicators. Previous work on Danish low-energy apartments [44] indicated that the thermal autonomy was mainly determined by the heat capacity of internal walls and heat losses from the external walls. Our work validated this finding for older single-family houses, too, which consist of less well-insulated building envelope and larger external envelope areas. If extensive refurbishments were to be applied to the building envelope, the effect of the thermal mass would be more pronounced.

The current case only investigated the residential building stock and specifically single-family houses. Thus, the building sample was very homogeneous. It should be pointed out that the investigated building stock did not include low-energy or nearly-zero energy buildings, which would have even longer thermal autonomy potential due to their very well-insulated building envelope. Furthermore, no apartment blocks or multi-family buildings were modelled in the current study, which would have lower thermal losses due to decreased external envelope area, leading to potentially higher heat flexibility. If different building typologies had been included, the thermal autonomy results could have been different, resulting in a different triggering of DSM events on the system scale. Also, if commercial buildings are to be included in the analysis, the internal gains and the occupant schedules should be adjusted accordingly. In that case, high internal gains from employees and equipment could potentially create overheating problems especially in newer office buildings, which is a challenge that has to be addressed during the design phase. Hence, the duration and set-points of the preheating strategy would have to be adjusted accordingly, so that they do not lead to very high and uncomfortable internal temperatures. It should be pointed out that this analysis focused only on the heating demand and the heat flexibility that could be provided to the district energy system due to the cold climate. No mechanical cooling is installed in the majority of residential buildings in Denmark. However, in warmer climates, district cooling is one of the promising solutions for increasing energy efficiency of system [45]. Thus, if a warmer climate had been studied, the thermal flexibility from a cooling perspective would have been relevant, too, as a demand side management technique.

There are several refinements, which could be assessed in the future. First, the simulation strategy we adopted was to return to the operative temperature as quickly as possible after the DSM event. This was facilitated by the cold ambient temperature and the relatively short overheating periods, which led to fast discharging of the thermal mass.

However, one could try to assess the performance of buildings if much slower temperature increase would be adopted. However, the latter needs to be balanced taking into account the expected thermal comfort, too.

Second, a future scenario with much more excess heat, solar thermal, heat pumps, geothermal and other renewable (and possibly intermittent) supply sources in the district heating grid could be analysed. Having more options and capacities of low operational cost technologies in the system could increase the activation of thermal mass for storage in order to avoid the utilization of high operating cost technologies.

Third, as the literature review showed that nearly zero energy buildings have very long autonomy times, one could try to assess the impact of utilizing the thermal mass for storage in a system with a very large share of nearly zero energy buildings. The latter system could represent newly built neighbourhoods connected to DH systems. According to [44], the thermal autonomy times of newly-built low-energy apartments in Denmark could exceed 15 h with a 4 h-preheating strategy, similar to our CO_4hPH.

Fourth, the system optimization model currently does not have the possibility of dynamic modelling of the operation of the DH grid. Hence, one of the future research pathways could be soft-linking of the current system optimization model with some of the dynamic models of the DH grid operation. The latter could make results robust for a wide range of operational cases.

Implementing smart controllers in district heating grid on very large scale is a significant feat. Thus, one potential implementation strategy would be to implement it when building refurbishments take place. That would reduce the installation costs and implement the controllers in the buildings that would have longer thermal autonomy times, after being refurbished.

6. Conclusions

This study investigated the potential of thermal building mass for storage in district heating systems. It was conducted as a two-stage analysis, where building performance simulations were run followed by a system optimization analysis. The building stock of Sønderborg was characterized by six archetypes that represented the 60% of single-family houses in the area. The results were evaluated on basis of two flexibility indicators: thermal autonomy potential that was defined during a heat supply cut-off while the internal temperature did not fall below 18 °C and the savings in heating demand compared to the reference case. A third indicator was used to evaluate the economics of the system. Three different strategies were investigated: (i) a heating cut-off for a certain number of hours, and preheating of (ii) two or (iii) four hours followed by a heating cut-off. The heating cut-off resulted in energy savings in all archetypes compared to the reference case, as expected. The effect of preheating control up to four hours was found to affect positively the heat flexibility potential of buildings, but should be evaluated individually for each archetype. The experiment of the cut-off was implemented on a cold and grey day, so that the effect of additional gains, such as solar gains, was not considered, while transmission losses through the building envelope were increased. This choice gave a pessimistic prediction to our results. The peak loads that were created after the

heating cut-off were mostly determined by the capacity of the heating system (i.e. hydronic radiators) and the duration of the cut-off, which determined the internal temperature. It was concluded that the highest potential for utilization of building thermal mass is provided by houses built after the 1980s, which have well-insulated building envelope and thus, have lower transmission losses. Furthermore, the thermal autonomy potential is better described by the total heat loss coefficient of the building envelope and less by the time constant during these cold and cloudy weather conditions, since heat losses were found to be more dominating in the specific buildings than the embedded thermal mass.

Operational savings in the DH system occurred in all the cases when thermal mass for storage was utilized. The economic savings in operational costs of the district heating system of the city of Sønderborg were in the range of 0.7%–4.6%, not taking the cost of smart controls into account. It would be feasible to invest up to 261 EUR per household in the installation of smart controls. The scenario carried out for the year 2029 showed that the benefits of using the thermal mass for storage are much greater in the future than in the current district heating system, due to the larger capacities of intermittent generation that can be successfully integrated in the district heating supply. Moreover, load shifting that is made possible with activation of thermal mass for storage allows for larger load factors of capital intensive-low operating cost technologies, such as central heat pumps.

One of the sensitivity analyses showed that the large-scale pit thermal energy storage is complementary to the thermal mass for storage, as the former is mainly used for seasonal shifting of load and the latter one for intra-day shifting of load.

All the scenarios showed that the thermal mass for storage allowed more solar thermal district heating to be effectively utilized. The most significant energy savings originated from the less utilized central gas boilers, as well as biomass boilers in the CO_2hPH_2029 scenario.

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Nomenclature

- $CO_2.inten_j$ CO_2 intensity of a certain technology or energy within the system boundaries, ton/MWh
 CO_2_j Costs of CO_2 emissions, €/ton
 $dies.imp_k$ Price of import of diesel in a specific hour, €/MWh
 $el.imp.exp_k$ Price of import or export of electricity in a specific hour, €/MWh
 $fix.O\&M_i$ Fixed operating and maintenance costs of energy plants, €/MW
 $fuel_j$ Fuel cost of specific energy type, €/MWh_{fuel}
 $gas.imp.exp_k$ Price of import or export of gas in a specific hour, €/MWh
 $lev.inv_i$ Levelized cost of investment over the energy plant lifetime, €/MW

- $petr.imp_k$ Price of import of gasoline in a specific hour, €/MWh
 x_i Capacity variables of energy plants, transmission grid and gas grid, MW
 x_j Generation capacities of energy plants (8760 variables for each energy plant, representing the generation in each hour during the one year), MWh
 x_k Import or export across the system boundaries of different types of energy (8760 variables per one type of energy, representing the flow in each hour during the one year), MWh
 η_j Efficiency of technology, MWh_{energy}/MWh_{fuel}
 T Operative temperature [°C]
 Q Heating demand of building after the applied strategy [Wh]
 Q_{ref} Heating demand of building under normal operation of heating system
 CO Heat supply cut-off strategy
 CO_2hPH Heat supply cut-off strategy with a 2 h preheating
 CO_4hPH Heat supply cut-off strategy with a 4 h preheating

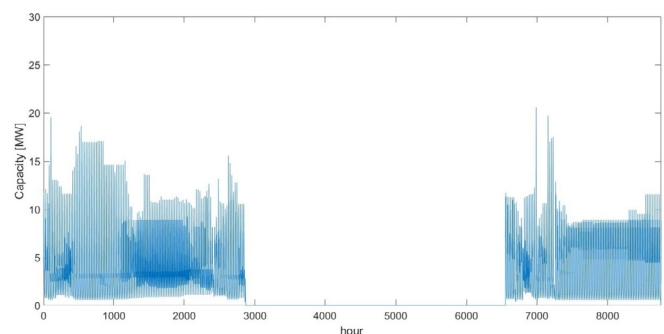
Appendix A

Generation of different plants in reference cases for the year 2015 and 2029.

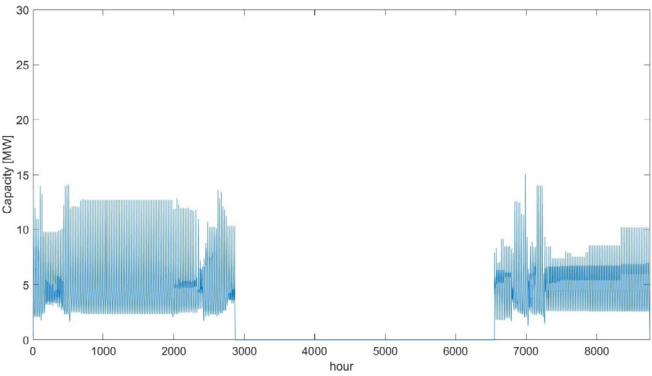
	Reference (2015) [MWh]	Reference (2029) [MWh]
Solar heating	3362	30,683
geothermal + biomass ab. Heat pump	77,930	60,108
biomass boilers	27,034	95,593
waste CHP heat	170,346	174,637
gas CHP heat	17,833	0
gas boilers	80,184	0
heat pumps	0	65,503
Wind turbine	37,488	454,875
PV	13,150	54,101
el grid import	334,300	20,030
el grid export	329	242,455
waste CHP ele	38,366	39,333
gas CHP ele	20,265	0
gas import	602,207	169,274
gas export	0	0
gasoline import	253,169	253,169
diesel import	253,169	253,169

Activation of cut-off events on hourly resolution in different scenarios:

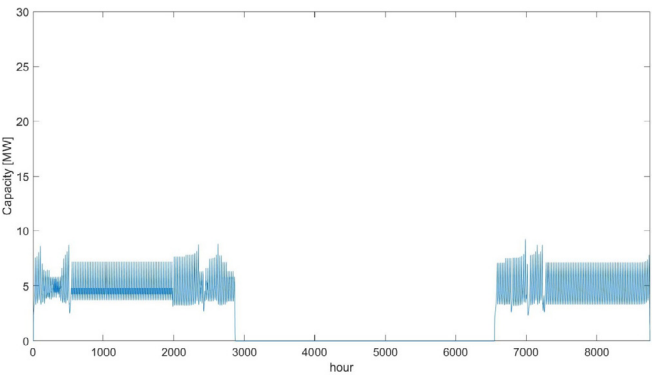
CO scenario:



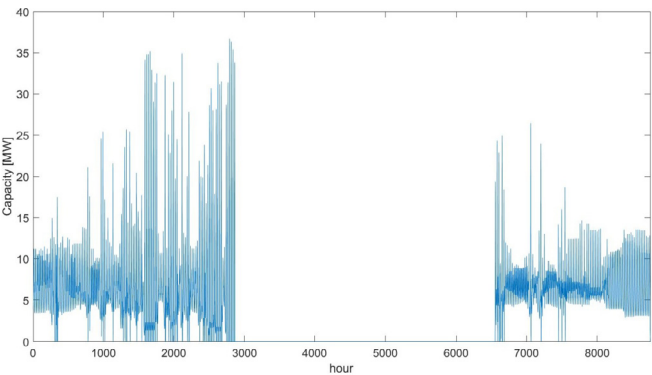
CO₂hPH scenario:



CO₄hPH scenario:



CO₂hPH₂₀₂₉ scenario:

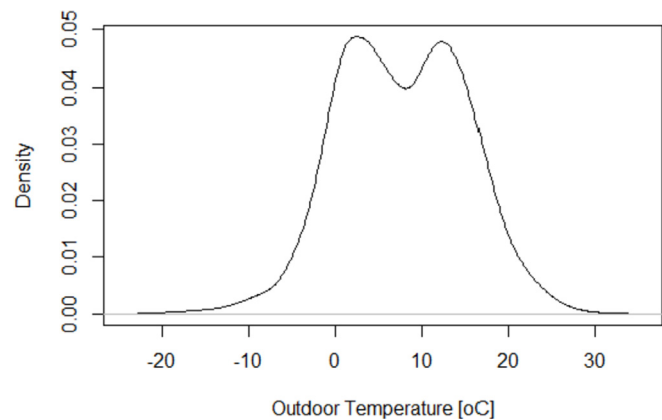


Appendix B

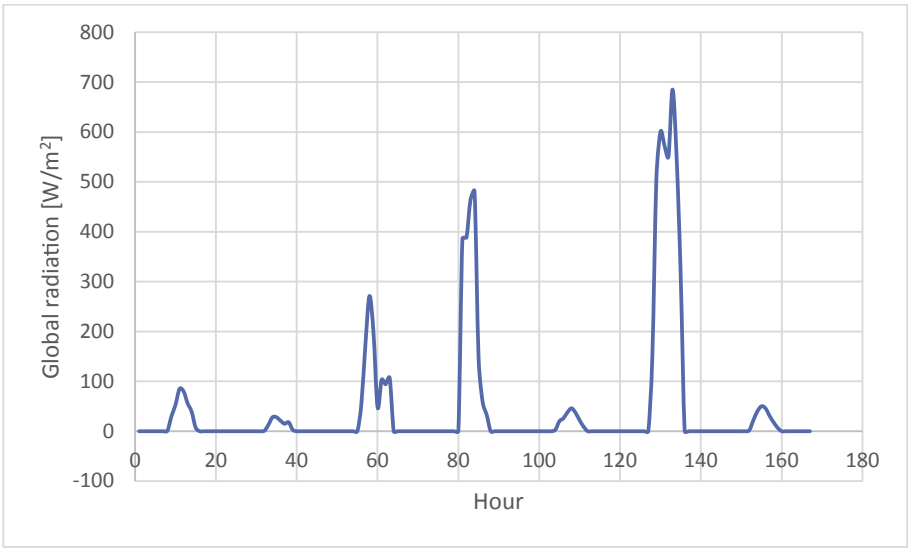
Monthly degree-day values for a year according to the given Danish climate file:

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
536	533	463	355	177	95	60	50	126	237	324	469

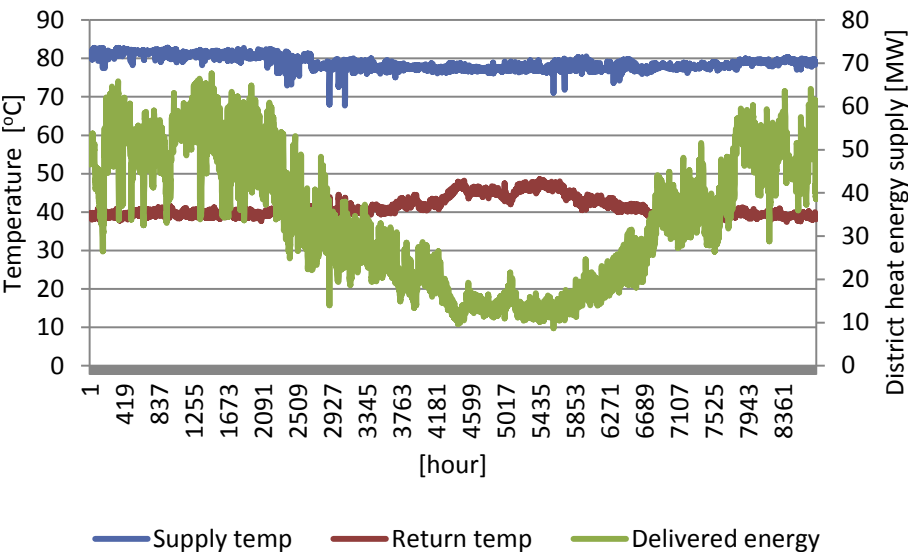
Annual outdoor temperature distribution:



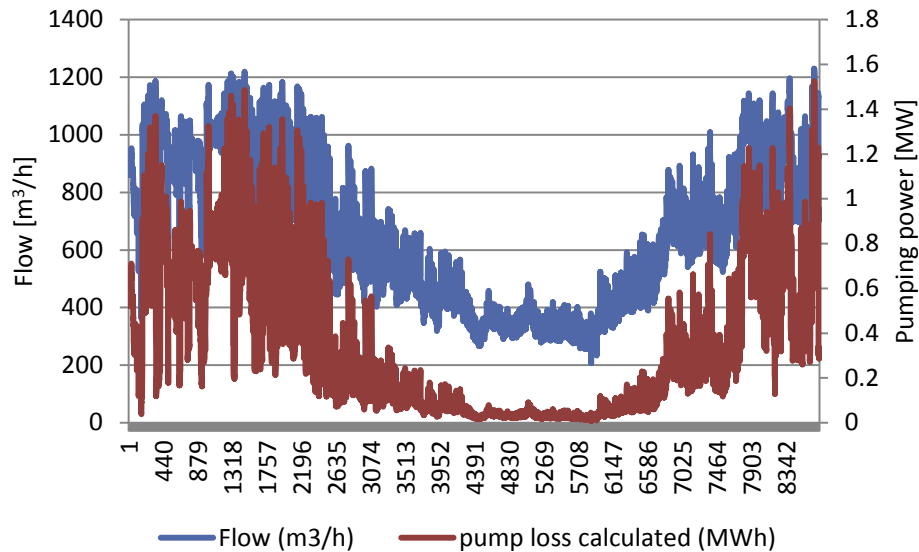
Global radiation amount for an exemplary week in January:



Hourly supply and return temperatures, as well as total delivered district heating energy to the end users, obtained from Sønderborg Fjernvarme (the operator of the DH grid):



Hourly volume flow (obtained from Sønderborg Fjernvarme) and estimated hourly pumping demand in the DH grid (total yearly pumping electricity demand is equal to the 1% of the final DH energy demand, in line with the pumping energy demand reported in Ref. [46]):



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Paper 8 - Influence of different technologies on dynamic pricing in district heating systems: Comparative case studies

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Influence of different technologies on dynamic pricing in district heating systems: Comparative case studies

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ABSTRACT

District heating markets are often dominated by monopolies in both Denmark and Finland. The same companies, often owned by local municipalities, are usually operating both supplying plants and district heating networks, while the pricing mechanisms are rigid, often agreed upon for one year in advance. The mentioned ownership scheme may cause problems, when one tries to gain a third party access in order to deliver excess heat or heat from cheaper heating plants. In this paper, two case studies were carried out to simulate the district heating systems based on dynamic pricing. Case studies were carried out for Sønderborg, Denmark and Espoo, Finland. The results showed that dynamic pricing fosters feeding the waste heat into the grid, as dynamic pricing reduced the total primary energy consumption and CO₂ emissions in both case studies. In the best scenarios, the weighted average heat price decreased by 25.6% in Sønderborg and 6.6% in Espoo, respectively.

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1. Introduction

During the last decade of the 20th century, the European Union (EU) decided to push for liberalization of energy markets of its Member States. The decision mostly referred to power and gas markets. A clear distinction was made between competitive parts, such as electricity generation and supply, and non-competitive parts, such as energy transmission and distribution. One important goal of the transition was to oblige the operators of transmission and distribution systems to grant equal access to the infrastructure to all the interested parties [1].

District heating (DH) sector was left outside of the immediate scope of the energy markets liberalization and different Member States approached it differently. Sweden is the country that went the furthest concerning the DH markets liberalization. Recent research showed that even though DH companies are supposed to be commercial in Sweden, the cost-based approach is still dominating over market pricing mechanism [2]. Furthermore, the authors concluded that still after 10 years from the initiation of the DH

markets liberalization, Swedish integrated market for heat has not yet evolved [2]. On the other hand, DH systems in Denmark, both energy generation facilities and infrastructure, are still largely owned by local municipalities. Notable exceptions are the DH systems of Copenhagen and Aarhus which have some sort of dynamic pricing [3].

In Finland, DH systems are natural monopolies inside network, i.e., there is only one DH operator in a network, typically a municipal company, and customers cannot choose their DH supplier. However, customers often have no obligation to connect to the DH network in Finland; they can rather freely choose from different heating technologies. In Finland, DH pricing has typically been rigid and pricing for customers has been based on connection, capacity and energy fees. There has been some development in DH pricing in recent years and some DH companies offer a seasonal-pricing option, in which energy fees are lower in summer and higher in winter, alongside the classical rigid pricing structure. However, neither of these pricing methods represent DH production costs accurately [4]. Opening DH markets has been identified as one of the key aspects to tackle the challenges caused by new European regulations, which are affecting energy production and energy efficiency in Finland [5]. In March 2018, Fortum announced that they are going to progress with opening of DH networks in Finland by announcing publishing of daily waste heat prices on

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their web sites, starting from spring 2018 [6].

A review of different pricing methods for DH has been presented in Ref. [7]. The authors suggested that marginal pricing would have various benefits, including better representation of production costs and reflecting the heat markets as well as motivating the suppliers to reduce the costs of heat production. However, the authors stated that marginal costs could be hard to calculate. Sun et al. proposed two methods for marginal pricing, mainly setting the electricity price and entropy drop, but their methods could not reflect the changes in different heat production technologies [8]. Dynamic pricing possibility for the Espoo DH, Finland, was studied in Ref. [4]. The authors concluded that the open heat market could be beneficial for all parties and that significant economic and energy savings were possible [4]. Different authors carried out a research on the possibility of regional heat market in Sweden [9]. The authors focused on the region dominated by energy intensive industries with a large waste heat potential and results showed that the payback time of integrating DH systems ranged from two to eleven years, depending on the scenario [9].

Industrial and individual consumers could become so called prosumers in the future, if the access to the DH infrastructure were granted to them under the fair pricing mechanisms. In that way, significant amount of waste heat from industry could be fed back to the grid, while excess capacity that consumers sometimes have could be better utilized. Based on a case study in Malmö, Sweden, prosumers with continuous cooling demand could have a notable impact in DH network [10]. The case study also suggested that there has been a prominent amount of low temperature heat available, which could be utilized in DH network [10]. Kimming et al. concluded that the vertical integration of local fuel producers into DH systems resulted in lower costs and emissions in the energy system [11]. Moreover, it was found that both the conditions of the energy market, as well as the type of the heat production system impacts the system emissions from the life-cycle perspective [12]. Furthermore, it was found that the industrial excess heat fed into DH system can be beneficial even when it causes reduced local electricity generation [12]. Another study identified a significant untapped potential of industrial waste heat on the case of Sweden DH systems, confirming that the Third Party Access legislation would be beneficial if adopted [13]. Finally, it was shown that even the introduction of individual prosumers is possible, based on technologies such as solar collectors and heat pumps, although it demands management and control of the issues such as locally lower heat supply temperature, as well as the local changes in velocity and differential pressure [14].

Most of the papers presented here have not studied the potential of dynamic pricing in the DH systems in a systematic manner. No paper that dealt with the marginal pricing in district heating adopted the pure marginal based pricing used in power markets. As it was shown in the literature review that several papers suggested to carry out a simulation of marginal based pricing, this paper filled that research gap. Furthermore, one of the papers detected that it is needed to model the impact of solar thermal collectors, heat pumps and thermal energy storage (TES) on DH markets [5]. In order to fill all of the gaps in the literature presented here, this paper aimed for answering the following research question:

“What is the potential effect of dynamic pricing based on marginal costs on DH systems?”

The approach used in this paper allowed more realistic evaluation of low marginal cost heat in different periods of the year, being especially relevant for evaluation of future DH systems, when

more low marginal cost heat is expected to be used, such as industrial waste heat and solar thermal energy. In order to make the results robust, two case studies were carried out, one for the DH grid in Denmark and one for Finland.

The paper continues with the Methods section, in which the potential mechanism of dynamic pricing in the DH systems is presented, and case studies description. In the Results section, the total turnover of the dynamically priced DH systems, weighted average marginal costs of the heat generation and the CO₂ emissions in different scenarios are shown. The results of the paper are put in the perspective of other DH systems in the Discussion section, together with a discussion on the major uncertainties about the assumptions used in this paper. Finally, the key points are summarized in the Conclusion section.

2. Methods

District heating supply and demand was simulated in similar fashion as the current electricity day-ahead markets operate, such as El-spot market on Nordpool. Heat demand in the DH system was taken as fixed, using the real data obtained for the year 2015. Heat supply was simulated based on the marginal cost of heat generation in each hour. The point where the heat supply and demand curves intersect is the price of heat set for that hour, as it can be seen in Fig. 1.

The marginal heat generation price included variable operating and maintenance costs (O&M), fuel costs, different fees and taxes, as well as the feed-in premium, if eligible. The latter means that only the costs that depend on the amount of energy generated (running costs) are included in the price formation. Capital costs, such as annualized investment costs, are not included in the bidding price formation as those costs are considered as sunk costs, once they have occurred. If one had decided to invest in an energy plant and a certain capacity was installed, the capital costs would need to be paid for no matter on the amount of generated energy. Thus, in the short-term, the operator of the plant will accept any price that is higher than the running costs of the energy plant.

Furthermore, concerning the cogeneration (CHP) plants, electricity income from el-spot market was deducted from the total heat generation costs, while the total fuel costs were included in the marginal price. Using the latter approach, a complicated division between fuels used for power and heat generation was

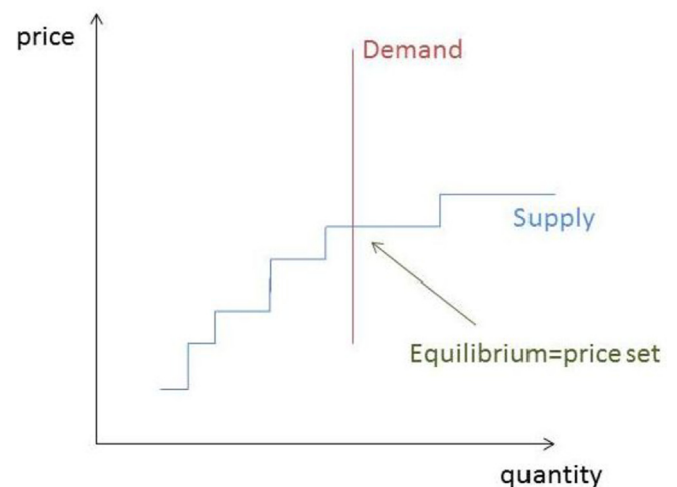


Fig. 1. A representation of the demand-supply curve in the simulated dynamic heat market (vertical demand curve represents the fixed heating demand that was assumed in each hour).

avoided. However, the latter approach can result in a bidding strategy that is not completely clear at first, i.e. high electricity prices will result in a high income for the CHP plant, which will consequently result in a lower marginal price set for bidding on the heat market. Hence, higher electricity prices, and higher corresponding income that will be deducted from the marginal heat offering price, the lower the marginal cost will be of the heat generation from CHP plant. The opposite also holds true, i.e. the lower the electricity price is achieved, the higher the heat marginal price will be offered to the market. Once again, investment costs in technologies were not taken into account when calculating marginal costs of heat production.

As the power market is much larger compared to the DH system potential markets, the influence of heat generation plants that consume or generate electricity on the day-ahead el-spot market was not modelled, i.e., it was assumed that there is no influence of them on the power market equilibrium price.

The indicators used for evaluation of the DH systems were CO₂ emissions and total yearly turnover. The latter two indicators were the output of the simulation of the dynamically priced DH systems, while the same indicators for the DH systems operated in the current way were obtained from the official websites of the DH companies.

In total, six different scenarios were developed for the case of Sønderborg and five different scenarios for the case of Espoo DH system. The simulations were carried out in Matlab. Moreover, a sensitivity analysis on the influence of electricity price changes was carried out and the results are discussed in the Discussion section.

2.1. Case study of sønderborg

The Sønderborg municipality covers the area of 496 km² and has a population of 75,000. Currently, the whole municipality has five distributed DH systems, although the connection of it proved to be feasible and economically viable [15]. The municipality aims for becoming CO₂ neutral by 2029, rapidly increasing its share of renewables in power, heat and gas sectors [16]. For the year 2013, the total CO₂ emissions were around 530 Mt [17], leaving significant challenges for the transition towards carbon neutrality. The total gross generation in DH systems in the municipality amounted to 488 GWh in 2013 [17]. The list of the heat generation plants that are operating in the DH system can be seen in Table 1.

As it can be seen from Table 1, gas CHP and gas boilers were dominating the heat generation mix. Recently, solar district heating (SDH) gained momentum and it is expected that its share will significantly rise in the future. The marginal cost of the heat production of different plants can be seen in Fig. 2.

Several issues concerning Fig. 2 need to be clarified. First, the price of electric boiler and heat pump heat generation is not constant as the electricity needed to drive them needs to be bought on the wholesale market where prices change on hourly basis. Thus, the Nordpool El-spot prices for the year 2015 were used [24]. Second, the cost of CHP plants is difficult to divide between the cost share of electricity generation and the cost share of heat generation. However, as the electricity sold on the day-ahead market was taken into account and deducted from the marginal costs of heat generation, this issue was not relevant anymore. Consequently, the prices were changing on hourly basis due to the different price obtained from the day-ahead el-spot market. In Fig. 2, presented total prices are the ones obtained by using the average electricity price as income for CHP plants, as well as the expenditure for electric boilers and heat pumps. Min ele price and Max ele price denote the marginal prices of different energy plants achieved for minimum and maximum electricity prices during the year, respectively. Third, it was taken into account that waste CHP plant receives a gate fee of 7.2 EUR/MWh of waste and further subsidy of 10 EUR/MWh of electricity sold.

The thermal energy storage (TES) sets its bids and offers in slightly different manner than the other heat generation plants. The marginal cost of the large TES is very low; however, the goal of its operation from the business-economic point of view is to buy the energy when the price is low and sell it when the price is high. In the case of Sønderborg, the considered technology was pit thermal energy storage (PTES).

The PTES was considered to be owned by third party in the scenarios, and thus the aim of the storage was not to minimize total production costs of the system, but rather to capitalize on price differences between different hours and maximize its profits. Storage bidding to the market could increase or decrease marginal prices of heat production, which would affect the costs or profits of storage. Storage made decision whether it should buy or sell heat depending on the marginal prices of each hour. Storage did not have a perfect foresight of the market. Table 2 presents the buy and sell offers of the storage in different time periods for the case of

Table 1

Heat generation capacity in the Sønderborg municipality [17] (Fuel efficiency values taken from Ref. [18] if not stated otherwise).

	Heat capacity [MW]	Power capacity [MW]	Fuel	Fuel efficiency
CHP Grasten	7.2	5.4	Gas	94% [19]
Boiler Grasten	14.5		Gas	96%
Boiler Grasten	12		Straw	80%
SDH Grasten	13		Solar collectors	—
CHP Broager	4	3.1	Gas	94% [19]
Boiler Broager	13.9		Gas	96%
SDH Broager	7		Solar collectors	—
CHP Nordborg	8.7	6.1	Gas	94% [19]
Boilers Nordborg	16		Gas	96%
CHP Augustenborg	4.9	3.8	Gas	94% [19]
Boiler Augustenborg	15.7		Gas	96%
Boiler Augustenborg	8		Electricity	99%
CHP Sønderborg	20	4.5	Waste	98% [20]
CHP Sønderborg	40	53	Gas	94% [19]
Boiler Sønderborg	100		Gas	96%
SDH Sønderborg	5.2		Solar collectors	—
Boiler Sønderborg	5.4		Bio-oil	95%
Geothermal + absorption heat pump	12.5		Geothermal and biomass driven heat pump	135% ^a
Total	308			

^a Biomass-to-heat efficiency. Geothermal heat is extracted at 44 °C after which biomass driven absorption heat pump is used to raise the temperature to 82 °C.

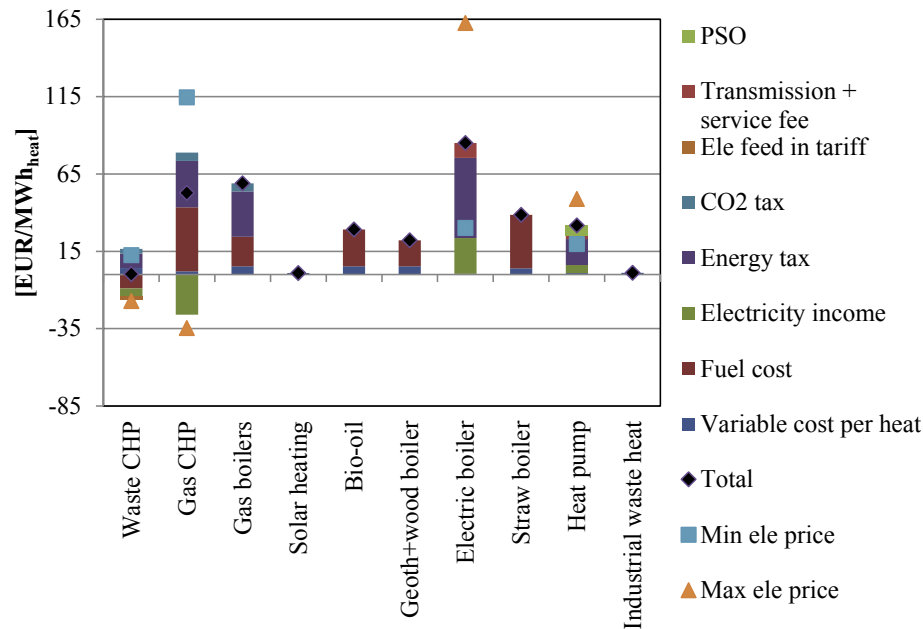


Fig. 2. Marginal costs of producing heating energy from different plants. Fuel costs taken from Ref. [21], biomass cost taken from Ref. [22] and taxes taken from Ref. [23].

Table 2

Buy and sell offers of the PTES in different periods - Sønderborg case.

	Hours 1-3416	Hours 3417-6812	Hours 6813-8760
Buying bid	10 EUR/MWh	5 EUR/MWh	50 EUR/MWh
Selling offer	15 EUR/MWh	23 EUR/MWh	58 EUR/MWh

Sønderborg. Marginal prices may shift within certain limits when the storage is utilized. This can cause dropping certain production technologies from the markets, e.g. natural gas HOBs. The storage utilization was optimized based on assumed marginal costs of other technologies. The latter resulted in a different buying and selling bids during different seasons in order to take advantage of the price arbitrage.

To clarify Table 2, the buying offer represents the maximum price that can be achieved for which the storage will still buy certain amount of heating. Similarly, the selling offer represents the minimum price that needs to be achieved in order for storage to sell the energy to the DH grid.

In order to model the current and the future potential influence of the dynamic heat markets on the heat generation system, six different scenarios were developed. The first scenario represented the model of the heat generation portfolio in the Sønderborg municipality as it was in the year 2015. The second scenario incorporated the waste heat potential close to the Gråsten and Broager DH parts. The potential of excess heat being fed to the DH grid was pinpointed in the case study on industrial waste heat potential in Sweden [13], industrial waste heat potential in the municipality of Sønderborg [15] and the waste heat potential from data centers in Finland [25].

The third scenario took into account further possibility of expansion of the SDH in order to simulate the impact of the increased share of the low-marginal cost producer could have on the dynamic heat market. The latter technology was discussed in the DH perspective in several papers. Winterscheid et al. showed that solar thermal technology can be implemented in the existing network that does not undergo structural changes [26]. The potential of the same technology was also pinpointed for the case of

Latvia [27], as well as in centralized and distributed integration of solar heat [28]. All three mentioned studies pointed to the significant potential of the SDH in the future. Furthermore, the fourth scenario added a large-scale heat pump to the system. The role of large-scale heat pumps in the future DH systems was discussed in many papers. Lund & Persson mapped the potential heat sources for heat pumps in future low temperature district heating in Denmark [29], while Münster et al. showed the role of heat pumps in combination with other technologies in the district heating [30]. Nevertheless, Dominković showed the potential role of large-scale centralized heat pumps in future district heating networks [31]. All three studies concluded that the potential of the heat pumps is much larger than they are currently being utilized.

The last two scenarios were constructed to assess the influence of large PTES, the technology choice for large thermal energy storage in several studies, for example in Ref. [31]. The efficiency of PTES of 95% was assumed [18]. In the Sønd PTES scenario, the impact of the PTES was assessed on the 2015 reference system, while in the Sønd ALL scenario the PTES technology was added to all the other technologies, i.e. increased SDH, heat pumps and industrial prosumers. Overview of the differences between scenarios can be seen in Table 3.

2.2. Case study of Espoo

Espoo is a city located in Southern Finland and it is Finland's second largest city with over 270,000 inhabitants. The Espoo DH network is operated by Fortum Ltd, and 70% of the inhabitants in Espoo were connected to the DH network in 2015 [32]. Fortum is one of the few non-municipal DH network operators in Finland. Nowadays, the Espoo DH network also covers the municipalities of Kirkkonummi and Kauniainen and the length of the network is over 1000 km in total [32]. Table 4 presents heat production units and capacities in Espoo DH network in 2015. Current heat production capacity in the Espoo DH network is dominated by fossil fuel based heat production units, namely coal and natural gas CHPs. Opposite to the Sønderborg case, Fortum operates far larger CHP plants, which are mostly utilized for baseload heat production. In addition to plants presented in Table 4, Fortum has built a TES, namely hot

Table 3
Scenarios for Sønderborg DH network.

	Heat demand, electricity prices, fuel costs	Additional heat supply
Sønderborg reference (Sønd ref)	Based on the 2015 data	
Sønderborg industrial waste heat (Sønd WH)		33.89 GWh/year
Sønderborg solar district heating (Sønd WH SDH)		Sønd WH + Solar district heating capacity increased to 179 MW
Sønderborg central heat pump (Sønd WH SDH HP)		Sønd WH SDH + HP capacity of 25 MW _t
Sønderborg reference with pit thermal energy storage (Sønd PTES)		Sønd ref + PTES capacity of 750 MWh and 20 MW
Sønderborg all additional technologies (Sønd ALL)		Sønd WH SDH HP + PTES capacity of 750 MWh and 20 MW

Table 4
Heat generation capacity in Espoo DH network [32]. Fuel efficiency values taken from Ref. [4].

Plant	Heat capacity [MW]	Power capacity [MW]	Fuel	Fuel efficiency
CHP Suomenoja 1	162	75	Coal	90%
CHP Suomenoja 2	213	234	Natural gas	90%
CHP Suomenoja 6	80	49	Natural gas	90%
Boiler Suomenoja 3	70	—	Coal	85%
Boiler Suomenoja 7	35	—	Natural gas	85%
Boiler Kivenlahti	65	—	Heavy Fuel Oil (HFO)	85%
Boiler Tapiola	160	—	Natural gas	85%
Boiler Vermo	80	—	Natural gas	85%
Boiler Kaupunginkallio	80	—	Light Fuel Oil (LFO)	85%
Boiler Otaniemi	120	—	Natural gas	85%
Boiler Juvanmalmi	15	—	Natural gas	85%
Boiler Kalajärvi	5	—	LFO	85%
Boiler Vermo	45	—	Natural gas	85%
Boiler Masala	5	—	Natural gas	85%
Boiler Kirkkonummi	31	—	Natural gas	85%
External heat	12	—	—	—
Heat pump Suomenoja	40	—	Electricity	COP 3.5
Boiler Vermo	35	—	Bio-oil	85%
Boiler Kivenlahti	40	—	Wood pellets	85%
Total	1418			

water storage tank, next to Suomenoja CHP plants with a capacity of 110 MW and an energy content of 500–800 MW h. The storage operates on a short-term basis, e.g., hourly or daily level. The storage started operation in the end of 2015, and thus it was not considered in our reference case, but as an additional scenario.

In the near future, Fortum is seeking new solutions to cut both production costs and emissions of DH production and they are aiming towards carbon-neutral DH production by 2030 in Espoo. In the last few years, Fortum has replaced fossil fuel based DH production in Suomenoja and Vermo with bioenergy, e.g. bio-oil and wood pellets. In order to increase profitability of DH, Fortum has been studying multiple novel solutions in Finland, such as demand side management of DH in an office building in Otaniemi, Espoo [33]. As a future source of industrial waste heat, Fortum is planning to utilize waste heat from data centers (DCs) [34]. Fortum has signed a letter of intent to utilize waste heat from Telia's 24 MW IT-load DC, which is expected to produce 200 GWh of heat annually [35]. There are also other plans to further utilize DC waste heat in Espoo DH network as Fortum has agreed to invest in heat pumps to utilize 10–15 GWh of waste heat from Ericsson's DC in Kirkkonummi [36].

In Fig. 3, the marginal costs for different heat generation technologies in the Espoo DH network are presented. There are few issues in Espoo case, which need further clarification. First, similarly to the Sønderborg case, CHP production depends on el-spot prices, and thus revenues from electricity sales were deducted from CHP heat production costs. In Finland, CHP plants do not pay taxes for electricity production and they pay taxes only for 90% of the heat fed into DH network. In addition, CHP production has

additional benefits as the carbon dioxide tax for fossil fuels utilized in CHP is only 50% compared to other consumption of the fuel in question, e.g. using coal in heat only production. Second, costs for heat pumps and DCs include el-spot price, electricity taxes and electricity transmission fees. Taxes and transmission fees for the Suomenoja heat pump and DC are summed up in tax column in Fig. 3. Finally, the price for the current external heat in Espoo DH network is confidential and thus, it was estimated at a very low price. As the exact costs were not available, the current waste heat was excluded from Fig. 3. Max and min electricity price scatters represent the maximum and minimum marginal costs for technologies, which are affected by electricity prices. El-spot system prices in Finland varied between 0.32 and 150 EUR/MWh in 2015 [24]. The total average marginal cost includes all the costs and income from electricity sales.

As previously mentioned, possibilities for marginal pricing of DH in Espoo DH network have been simulated in Ref. [4]. However, there are new plans for novel, large-scale heat supply, e.g. DC and a large-scale geothermal heat plant and thus, the effects of these plants on heat production require attention. These two projects together have been estimated to be able to supply approximately 20% of the DH demand in Espoo and both are expected to be producing heat by the end of 2019.

Five different scenarios were developed for the Espoo case. All of the scenarios were simulated with normalized hourly heat demand, hourly electricity prices and fuel costs in 2015. First, the reference scenario for 2015 was developed by utilizing heat production units presented in Table 5 to represent the current system. The second scenario considered the inclusion of TES to the

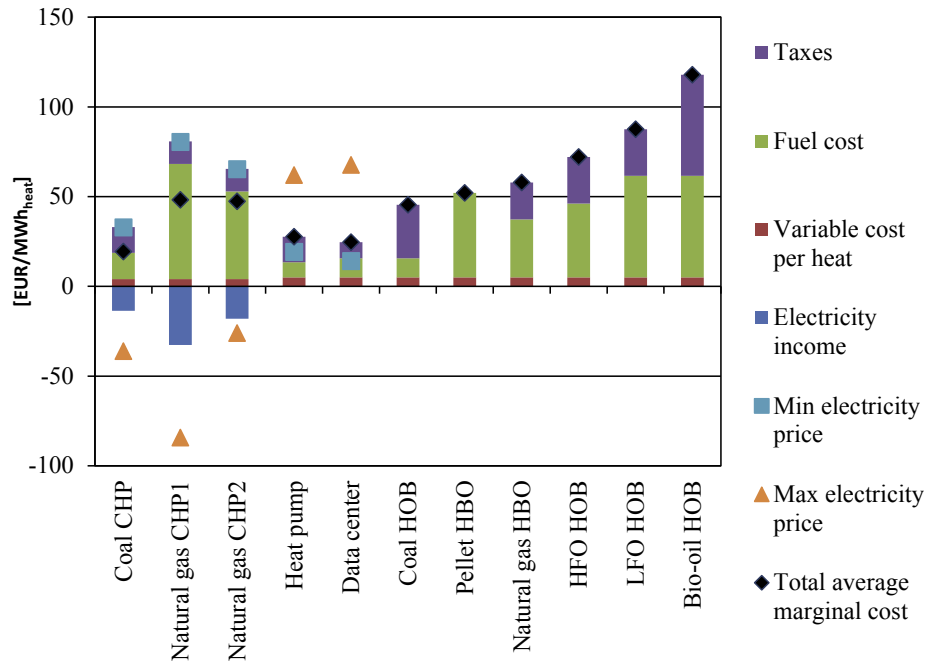


Fig. 3. Marginal costs for different technologies in Espoo DH. Electricity spot-prices taken from Ref. [24]. Taxes and fuel costs for coal, natural gas and biomass, as well as taxes and transmission costs for electricity, taken from Ref. [37]. Taxes and fuel costs for oil products taken from Ref. [38].

Table 5
Scenarios for Espoo DH network.

	Espoo reference REF	Espoo reference with storage REF + STOR	Espoo waste heat WH	Espoo geothermal with waste heat GEO + WH	Espoo geothermal with waste heat and storage GEO+WH+STOR
Heat demand, electricity prices, fuel costs	Based on 2015 data	Based on 2015 data	Based on 2015 data	Based on 2015 data	Based on 2015 data
Additional heat supply	—	TES 110 MW (800 MWh energy content)	200 GWh waste heat per year, monthly changing load	40 GW geothermal capacity, constant load + DC waste heat	40 GW geothermal capacity, constant load + DC waste heat + TES 110 MW (800 MWh energy content)

reference system. The third scenario considered industrial waste heat utilization, which in this case was waste heat from Telia's DC. The fourth scenario considered both Telia's DC waste heat and, in addition, St1's and Fortum's large-scale geothermal pilot in Espoo, which has been further discussed e.g. in Ref. [33]. The fifth scenario includes both waste heat and geothermal heat alongside TES.

Geothermal pilot is expected to produce approximately 10% of the DH demand in Espoo by drilling two holes up to 7 km and utilizing 120 °C source of heat. The geothermal plant is estimated to produce heat at a constant 40 MW load.

Possibilities and requirements, as well as different projects, for DC waste heat utilization in DH have been studied for example by Wahlroos et al. [34]. Waste heat production from DC is depending on cooling system in the DC. Typically, DCs produce more waste heat when air temperatures are higher, causing more waste heat to be available during summertime [25]. Waste heat can typically be captured at 35–40 °C in air-to-liquid heat recovery systems. In order to efficiently utilize DC waste heat in DH, waste heat temperature needs to be increased to sufficient temperatures for DH, i.e., supply side temperatures (75–115 °C) or return side temperatures (approximately 60 °C) in Finland. Heat pumps can be used to increase temperature of the heat, while coefficient of performance (COP) depends on the temperature difference of actual priming. DCs should be located close to DH networks in order to be connected to DH networks without significant investment costs [25].

Since Fortum has estimated that Telia's DC will produce 200 GWh annually, this amount was divided on a monthly basis based on average monthly DC electricity consumption in an actual DC. Hourly pattern of waste heat production was not available. Thus, it was estimated that the waste heat availability is continuous during each hour within a month. As a result, the hourly waste heat load varied between 20.85 and 26.75 MW in different months. It was assumed that the heat temperature has been elevated with a heat pump up to 85 °C. The COP value for the heat pump was assumed to be 2.8, which would make it technically possible for waste heat to be utilized in the supply side of DH system in Espoo. In Finland, DCs are considered as industrial electricity consumers and thus they have lower electricity taxation; however, the latter depends whether heat pump produces the cooling energy for the DC or not. The question of waste heat pricing has been further debated in discussion section.

In the case of Espoo, the TES was considered to be owned by third party and storage operated according to the same method as in the case Sønderborg. The efficiency of the TES of 95% was also assumed in the Espoo case. Table 6 presents bidding values for storage during different seasons of the year in the case of Espoo.

3. Results

The results of the dynamic price based heat market simulation

Table 6

Storage bidding strategy in the case of Espoo.

	Hours 1–2999	Hours 3000–5999	Hours 6000 – 8760
Maximum buying bid limit	48 EUR/MWh	33 EUR/MWh	48 EUR/MWh
Minimum selling offer limit	55 EUR/MWh	40 EUR/MWh	55 EUR/MWh

Table 7

Economic results in different scenarios.

Scenario	Total yearly turnover [mil EUR/year]	Weighted average marginal price
Sønd ref	23.99	49.58
Sønd WH	23.16	47.86
Sønd WH SDH	21.71	44.86
Sønd WH SDH HP	18.25	37.71
Sønd PTES	23.25	48.03
Sønd ALL	18.45	37.82

consisted of economic indicators and an environmental indicator. Economic indicators were the achieved heat price during the every hour of the year and the total yearly turnover in different scenarios, while the environmental indicator was represented by CO₂ emissions.

3.1. Case study of sønderborg

Six scenarios were carried out in total for the Sønderborg case. Weighted average marginal heat price, as well as the total yearly turnover for different scenarios can be seen in Table 7.

It can be seen that the weighted average marginal heat price decreased when additional low marginal cost heat producers were introduced to the system. Furthermore, although PTES bidding strategy reduced prices in certain hours and increased in some of the other hours, on average, it reduced the marginal heat prices in Sønd PTES scenario compared to the Sønd ref scenario and increased the marginal heat prices in the Sønd ALL scenario compared to the Sønd WH SDH HP scenario.

Fig. 4 presents the yearly generation of different technologies in different scenarios. Availability of the industrial waste heat caused all the other plants to reduce their outputs except the solar-thermal plant that was still maximally utilized. The largest decrease in output came from gas boilers.

In Sønd WH SDH scenario, the increased output of solar DH caused lower outputs of all the other plants in the system. Moreover, it has decreased the output of industrial WH for 27%, compared to the Sønd WH scenario. The latter was caused due to the competition of the very low marginal cost technologies during the summer time, when there was a lack of demand for the available low-cost capacity. This points to the possible conflict in the future when large amount of waste heat could be fed to the grid during the time when there is no strong demand for DH.

In Sønd WH SDH HP scenario, the heat pump (COP = 4.5) was significantly utilized, i.e. it fulfilled 20% of the gross DH demand during the year. Compared to the Sønd WH SDH scenario, the geothermal energy coupled with absorption HP, solar DH and industrial WH had the same output, while the other plants had lower outputs. The most notable decrease in the heat generation occurred in gas and straw boilers, i.e. their output reduced for 78% and 43%, respectively.

Furthermore, in Sønd ALL scenario, the PTES allowed for increased effective utilization of solar DH, increasing its effective output for 19% compared to the Sønd WH SDH and Sønd WH SDH HP scenarios.

Comparing the Sønd ref and Sønd PTES scenarios, one can note

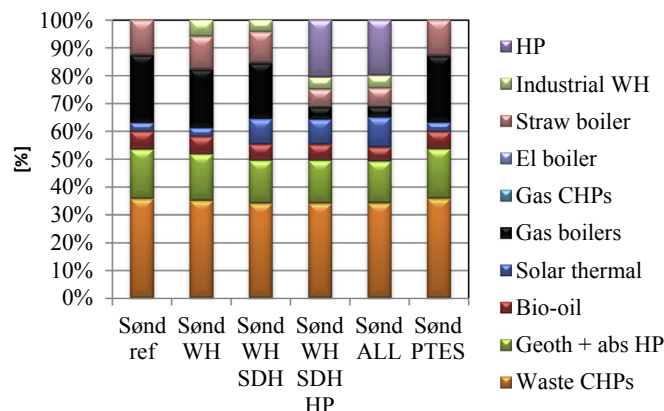


Fig. 4. Share of generation of different plants in scenarios. The total heat generation amounts to 484 GWh/year.

the influence of the large scale PTES on the current Sønderborg DH system. As the reference system did not have the excess capacity of certain low-cost generation technologies during certain periods of the year, the PTES caused only a minor change in operation of different plants. The main difference came from straw and gas boilers. The straw boiler increased its output for 2.3% while the gas boilers decreased their output for 1.6%.

Finally, Table 8 presents the CO₂ emissions from different heating generation plants. It can be observed that the scenarios that included waste heat from industry showed better performance in terms of CO₂ emissions. Even better performance was obtained when additional amount of SDH capacity and HP were introduced. It is interesting to note that the PTES increased the CO₂ emissions in both the scenarios, mainly due to the increased output of electric boilers. The reduction in CO₂ emissions between the Sønd WH SDH HP and Sønd ref scenarios was 36%.

Fig. 5 presents a price duration curve of the simulated heat market in the Sønderborg region. In Sønd ref, Sønd PTES, Sønd WH and Sønd WH SDH scenarios, approximately during half of the year the maximum price of 58.99 EUR was achieved, when gas boilers were on the margin. As the inclusion of HP significantly reduced the output of gas boilers, the maximum marginal price lasted for only 2065 and 1991 h in Sønd WH SDH HP and Sønd ALL scenarios, respectively. One can note from Fig. 5 that the addition of industrial prosumers with a low marginal price shifted the marginal price curve to the left, meaning that the overall prices of DH were reduced. Furthermore, in the third scenario when a significant increase in SDH occurred, on top of the addition of industrial prosumers, a marginal heat price curve further shifted to the left, as a consequence of further downward pressure on the marginal heat prices.

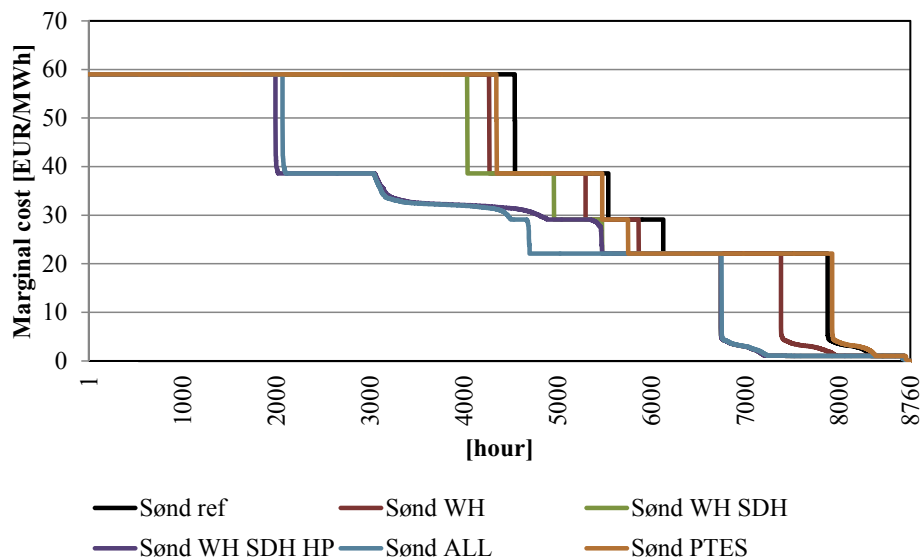
Comparing the Sønd ref and the Sønd PTES scenarios, one can note that the PTES reduced the amount of maximum marginal price and slightly increased the marginal prices during the period of relatively low marginal prices.

In the Sønd ALL scenario, during approximately 23% of the year achieved prices were less than 7 EUR/MWh.

Finally, the storage content in two scenarios that included PTES

Table 8CO₂ emissions from different heating plants [kt-CO₂]. CO₂ emission factors of different fuels taken from Ref. [21].

	Sønd ref	Sønd WH	Sønd WH SDH	Sønd WH SDH HP	Sønd ALL	Sønd PTES
Solar thermal	0	0	0	0	0	0
Bio-oil	0	0	0	0	0	0
Geoth + abs HP	0	0	0	0	0	0
Gas boilers	25	22	21	5	4	25
Gas CHPs	0	0	0	0	0	0
Waste CHPs	29	28	27	27	28	29
El boiler	49	49	49	27	35	61
Straw boiler	0	0	0	0	0	0
Industrial WH	0	0	0	0	0	0
HP	0	0	0	7	7	0
PTES	0	0	0	0	0	0
Total	103	99	97	66	73	115

**Fig. 5.** Simulated marginal costs in different scenarios in a descending order for the Sønderborg case.

is presented in Fig. 6

The total yearly turnover of PTES was 124,669 and 259,879 EUR in Sønd PTES and Sønd ALL scenarios, respectively. Relatively large capacity of the PTES was most notably used for transferring the heat from the summer time to the autumn and winter time, approaching the role of a seasonal storage.

3.2. Case study of Espoo

Table 9 presents the weighted average marginal heat prices and the total turnover in different scenarios for Case Espoo. As both geothermal and DC waste heat had low marginal costs, the total turnover decreased in both Espoo WH and GEO+WH scenarios compared to the reference scenario. Addition of storage bidding to the market further decreased the average price and the total turnover.

Fig. 7 presents price duration curves of the simulated heat market in the Espoo DH system. Curves represent simulated marginal prices in descending order in different scenarios. The natural gas HOB was typically the marginal technology, which determined the marginal heat production price (i.e. for natural gas HOB 57.8 EUR/MWh). Natural gas HOBs represented 32% (2831 h) of the marginal prices in Espoo GEO+WH+STOR scenario, and natural gas HOBs were even further dominating in REF and WH scenarios with shares of 41% (3627 h) and 45% (3975 h), respectively. Otherwise, duration curves are descending in small steps because natural gas

and coal CHP, as well as heat pumps, were affected by electricity prices, and thus their marginal prices fluctuated. The inclusion of both waste heat and geothermal heat shifted duration curves to the left, which implies that the overall marginal costs decreased. The operation of the storage affected marginal costs by shifting marginal costs from the most expensive hours to hours with lower costs when the marginal cost was high and vice versa when the marginal cost was low.

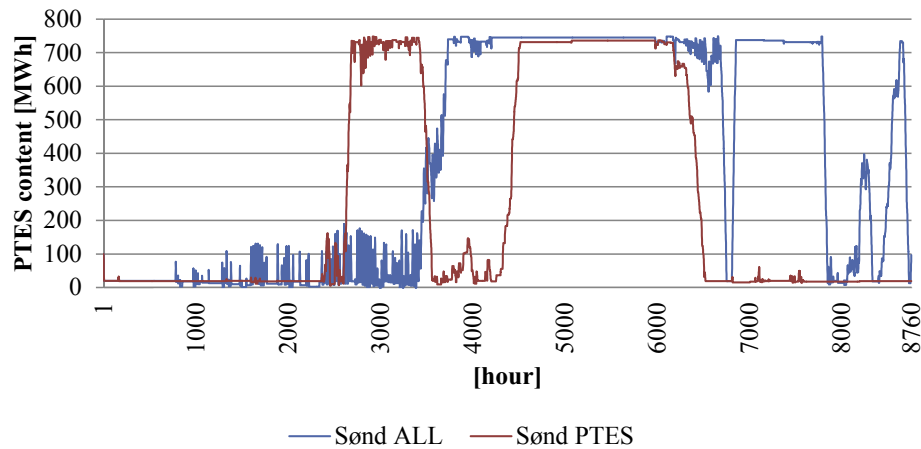
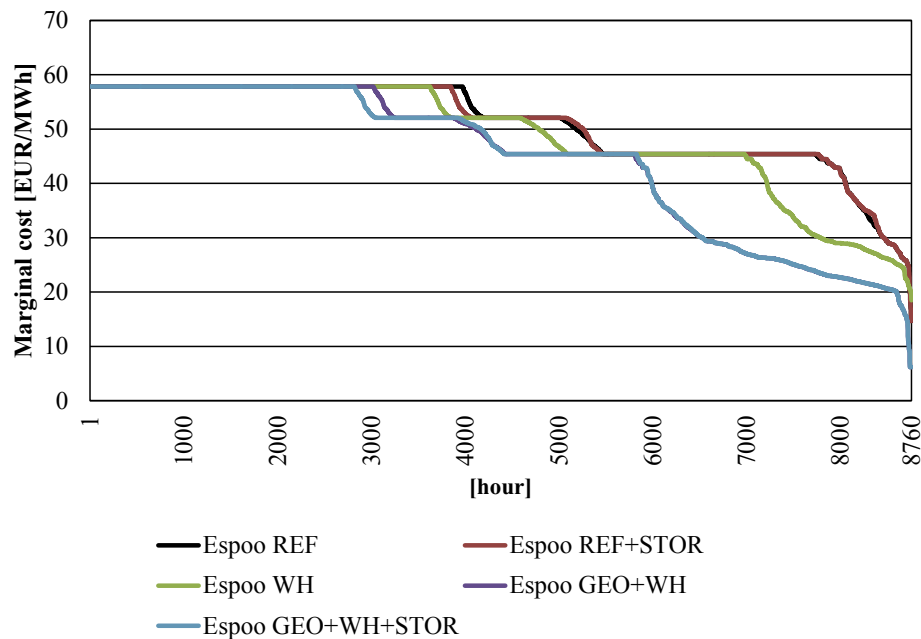
In the REF scenario, the marginal costs were over 45 EUR/MWh on 89% of the hours. Similar values for WH scenario and GEO+WH scenario were 80% and 66%, respectively. Fig. 7 shows that the amount of very low marginal cost hours increased significantly, especially in the GEO+WH scenario. In the reference scenario, the minimum marginal price was 14.7 EUR/MWh and marginal prices decreased below 30 EUR/MWh only during 295 h. In the GEO+WH scenario, minimum marginal prices were 6.2 EUR/MWh on few hours.

Fig. 8 presents annual share of heat production in different scenarios by different technologies. Heat production results show that production of all other heating plants decreased in Espoo WH scenario, while waste heat represented 7% of the total production. Furthermore, addition of geothermal heat, 15% of total production in GEO+WH and GEO+WH+STOR scenarios, further decreased operation of all other technologies. In addition, the inclusion of geothermal heat slightly affected waste heat production. It can be observed that the addition of waste heat and geothermal heat

Table 9

Economic results in different scenarios in Case Espoo.

	Espoo REF	Espoo REF+STOR	Espoo WH	Espoo GEO+WH	Espoo GEO+WH + STOR
Weighted average marginal heat price [EUR/MWh]	53.52	53.23	52.47	50.30	49.90
Total turnover [mil EUR/year]	127.18	126.65	124.70	119.52	118.75

**Fig. 6.** PTES content over the year in Sønd ALL and Sønd PTES scenarios.**Fig. 7.** Simulated marginal costs in different scenarios in a descending order in the case of Espoo.

replaced almost exclusively fossil fuel based heat production and pellet-based heat production. In the WH scenario, the heat pump production decreased by 4%, but in GEO+WH scenario the output of heat pump decreased by 21% compared to the REF scenario. Geothermal heat was utilized at the maximum capacity during all the hours. The introduction of storage decreased utilization of natural gas and pellet HOBs, but increased the use of natural gas CHP in both REF STOR and GEO+WH+STOR scenarios.

CO₂ emissions for different scenarios in the Espoo case are presented in Table 10. Additional waste heat in WH scenario decreased CO₂ emissions 4.6% compared to the REF scenario. In GEO+WH scenario, emissions were reduced by 17.6% compared to

the REF scenario. Emissions for current system were calculated by reported fuel consumption in 2015. Emission factors of different fuels in the Espoo case are presented in Appendix A. It must be noted that storage actually increased emissions in the simulations. This results from the fact that including storage in the model increased utilization of natural gas CHP plants, but decreased operation of wood pellet HOB, which was considered CO₂ neutral. Furthermore, due to the storage losses, the total DH production increased by over 3000 MWh in both storage scenarios.

Fig. 9 presents thermal energy content in TES in scenarios with storage in Espoo. Bidding structure was the same in both scenarios. In the GEO+WH+STOR scenario, the storage was able to utilize

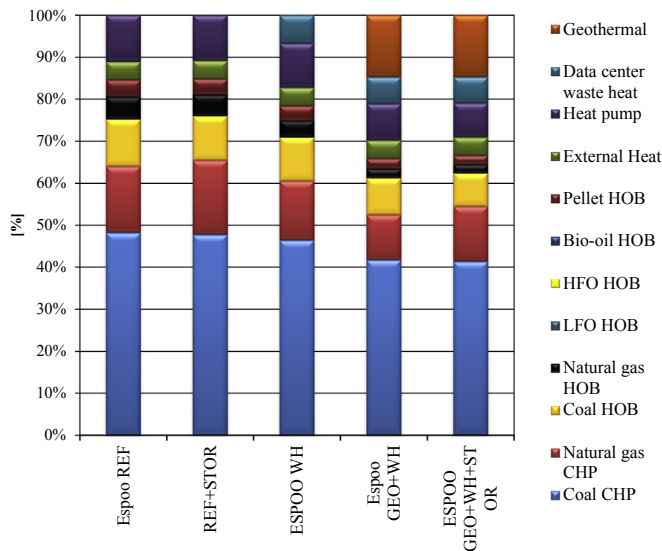


Fig. 8. Share of heat production of different technologies in scenarios. The total heat generation amounts to 2376 GWh/year.

cheaper hours during the wintertime to charge the storage more than in REF+STOR. However, the selling prices were not high enough during summertime and thus, the storage could not sell the heat to the market with current pricing structure in GEO+WH+STOR. The total yearly turnover of TES in case Espoo was 501,276 and 556,076 EUR in Espoo REF+STOR and Espoo GEO+WH+STOR scenarios, respectively.

4. Discussion

One can note from the results that the maximum marginal prices of heat in the Sønderborg DH system in the first four scenarios occurred during approximately half of the time, at 58.99 EUR/MWh. In the Sønd ALL and Sønd WH SDH HP scenarios, the same maximum price level occurred only during approximately one third of the year. The highest prices occurred during the winter period. During the autumn and summer periods, the prices were oscillating around the mid-level between the summer and winter prices. Finally, low demand during the summer caused very low prices, especially in Sønd ALL and Sønd WH SDH HP scenarios, in which during the 1998 h marginal heat prices were lower than 5 EUR/MWh.

In the case of Espoo, the highest marginal prices occurred in

wintertime when peak hourly load was over 800 MW and marginal prices were 57.8 EUR/MWh of heat. In Espoo, several HOB boilers and fuels, i.e. HFO, LFO and bio-oil, were not utilized in any of the scenarios, instigating that there is excessive HOB production capacity. The latter behavior could have been emphasized also due to the exclusion of the network constraints. Being the marginal heat technology for most of the hours, natural gas HOBs had the largest proportional decrease in both WH and GEO+WH scenarios, in which natural gas HOBs produced 58% less than in the reference scenario. Inclusion of both waste heat and geothermal heat resulted in decreased turnover of 2.0% in WH and 6.0% in GEO+WH scenario.

One can conclude from both Sønderborg and Espoo cases that the behavior of different plants causes similar effects on the dynamic prices of DH grids. During the winter periods when demand was high, prices are relatively stable at a high level. Autumn and spring were transitional periods during which prices gradually dropped (spring) or rose (autumn), following the changes in the demand for DH. Both case studies show that the inclusion of low marginal cost producers cause a shift of the marginal price curve to the left, putting a downward pressure to the prices. This behavior is especially visible in the Sønderborg case, which had larger capacities of low marginal cost producers in alternative scenarios. One should further note that the low cost of heat during the summer period causes operation of waste CHP plants to be unviable, potentially making problems for the handling of waste.

Fig. 10 presents the effects of sensitivity analysis on electricity prices in Sønd WH SDH HP and Espoo GEO+WH scenarios. Electricity prices affected the two DH systems differently due to the different heat production portfolio. The case of Espoo was more sensitive to changes in electricity prices than the case of Sønderborg, with high capacity of CHP electricity production and moderate heat-pump based production. A significant decrease of 50% in electricity prices increased marginal prices by 4%. If electricity prices were to decrease in the case of Espoo, it would increase marginal prices, as CHP production would become less profitable. Simultaneously, CO₂ emissions from heat production would decrease, as the coal-based CHP would generate less energy.

The case of Sønderborg shows slightly lower sensitivity to electricity price changes. For changes in electricity price of $\pm 50\%$, the changes in weighted average marginal prices were $\pm 2\%$, as heat pump, electric boiler and CHP units were rarely on the margin. By tracking CO₂ emissions in the case of Sønderborg, which was a dependent variable, one can note that significantly lower electricity prices can lead up to 6% of reduction in CO₂ emissions. The reason is that lower electricity prices result in lower generation from CHP plants driven by gas, as well as increased competitiveness of heat generation units driven by electricity, such as electric boiler and

Table 10
CO₂ emissions from different producers in Case Espoo.

	Espoo REF [kT-CO ₂]	Espoo REF+STOR [kT-CO ₂]	Espoo WH [kT-CO ₂]	Espoo GEO+WH [kT-CO ₂]	Espoo GEO+WH+STOR [kT-CO ₂]	Current system – calculated based on the fuel consumption [32]
Coal CHP	631.2	626.4	609.6	548.0	544.5	704.0
Natural gas CHP	157.6	178.2	141.6	109.6	134.4	58.5
Coal HOB	106.9	100.2	98.9	83.4	75.3	0
Natural gas HOB	29.5	28.5	22.2	12.4	11.9	28.3
LFO HOB	0	0	0	0	0	0.7
HFO HOB	0	0	0	0	0	24.9
Bio-oil HOB	0	0	0	0	0	0
Wood pellet HOB	0	0	0	0	0	0
External heat	0	0	0	0	0	0
Heat pump	13.2	12.9	12.6	10.4	9.7	16.5
DC waste heat	–	–	9.9	9.4	9.2	–
Geothermal	–	–	0	0	0	–
Total	938	946	895	773	785	833

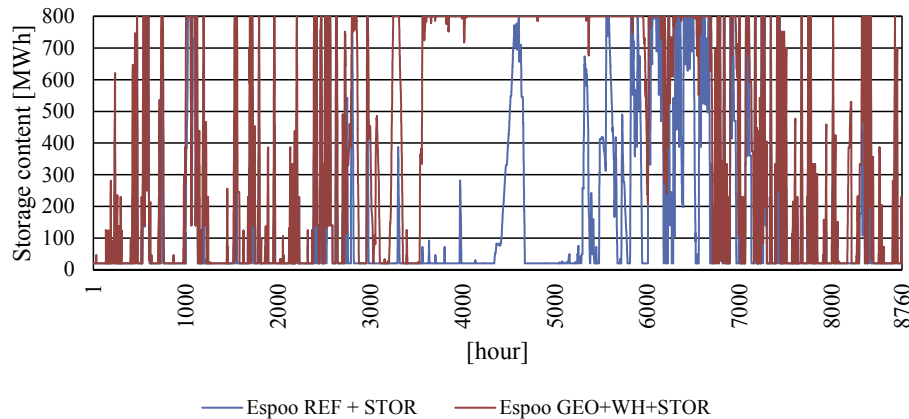


Fig. 9. Hourly TES content in scenarios Espoo REF+STOR and Espoo GEO+WH+STOR.

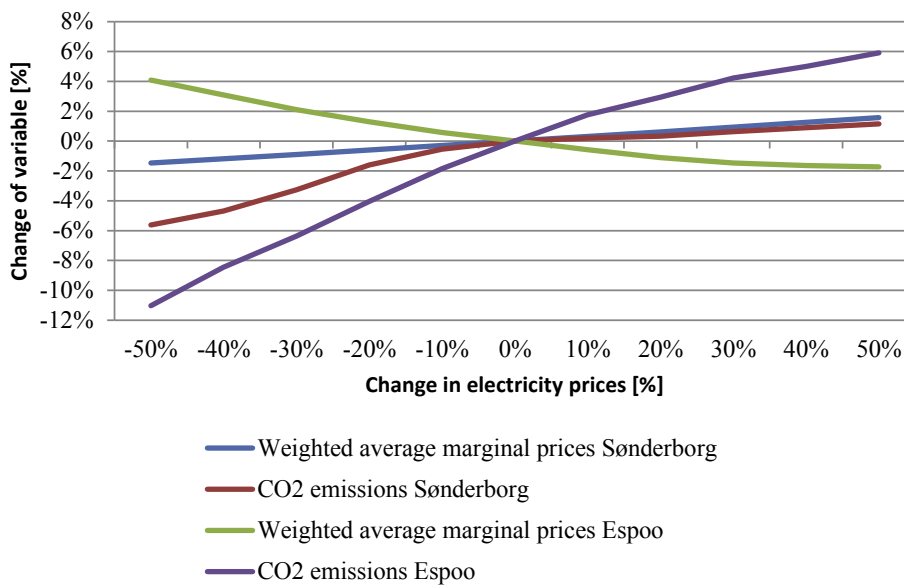


Fig. 10. The impact of electricity prices on the total heat turnover and marginal prices in Sønderborg and Espoo cases.

heat pump.

Due to the nature of marginal cost based pricing, investment costs were left out of the analysis. However, investment costs and technical constraints of different technologies may require attention. Some of the technologies are highly capital-intensive, e.g., large-scale geothermal, heat pumps and storages. If lots of capital-intensive technologies would be installed, adding some premium on top of the marginal cost bid would probably be needed.

Waste heat should be priced according to the equilibrium price set on the day-ahead market while the providers of the waste heat should bid according to their marginal cost. However, temperature levels of waste heat should be taken into account. Industrial waste heat from factories and industrial processes may have high enough temperatures to be directly supplied to supply side of DH network, but waste heat from DCs might be even lower than 35–40 °C, and thus could not be efficiently utilized if the temperature is not increased with heat pumps beforehand [39]. Therefore, temperature levels of available waste heat should be considered in further research.

There is a significant uncertainty originating from the storage bidding strategy. Storage was set to bid on an hourly level, without the knowledge on prices of future hours. With a short-term storage,

it can be assumed as a reasonable approach. Short-term storage typically capitalizes lower prices during the night and sells the heat during the day. In the case of Sønderborg, the large volume of the PTES (160,000 m³) made it closer to the behavior of a seasonal storage than a short-term storage. Operation of such storage should be separately optimized in order to achieve the maximum business-economic gains. However, relatively small amount of generators could make it relatively easy for the heat storage operator to significantly interfere with the marginal prices by offering different capacities during certain periods and the vice versa. In the case of Espoo, TES was mainly used as a short-term storage. However, the bidding strategy was not optimal as there were long periods when storage was not utilized, especially in the case with increased amount of low marginal cost heat production.

The latter point also leads to an issue in DH systems with a lack of suppliers. For the DH systems, the chosen cases are considered to be relatively competitive as DH systems often have only one base and one peak plant operated by the same company (municipality). In that case, the marginal pricing system would face issues, in the same time reducing the incentive for the suppliers to reduce the generation costs. One approach could be to make some benchmarking generation prices based on similar conditions and DH

generators in different competitive systems. Consequently, upon establishing the benchmark prices, a system of bonus and malus in prices could be introduced in the smaller systems. Integration of smaller DH systems in the marginal based dynamic pricing is a research topic that should be addressed in the future research.

Lower utilization of CHP may increase the electricity price, especially when there is high capacity of CHP production. Consequently, increased utilization of heat pumps increases electricity demand. The effects of decreased CHP production and increased demand of electricity on the electricity prices were not accounted in this study. Moreover, different external factors can influence DH demand and consequently the equilibrium price achieved, such as energy efficiency of building stock and weather conditions. The latter factors were outside of the scope of this study. Heat demand in this study was set from the historical time series, meaning that all the external factors were included implicitly via the set demand curve. However, in future research, it would be interesting to show the impact of heat demand dynamic on the potential development of the DH supply, both in the short term and in the long term, where the influence of heat demand on investments would be seen. Furthermore, the future research should address the possibility of using the similar approach to this study on district cooling markets, as the district cooling has a significant potential, especially in the currently developing regions located in the hot and humid climates [40].

Finally, as it was shown in this paper that the potential effect of dynamic pricing based on marginal costs on DH systems is significant, this research presents a valuable contribution to the development of the future DH systems, the ones that will be dominated by lower supply and return temperatures. The latter will further foster the integration of waste heat from different sources that generate low quality (low temperature) heat, whose potential impact on the DH market needs to be taken into account.

5. Conclusions

To conclude, results indicate that utilizing waste heat decreased both total heat production costs and CO₂ emissions. The addition of low marginal cost heat production decreased marginal prices close to zero during the summertime in both scenarios. To avoid providing too large prices for third party heat supply, dynamic heat markets are a viable solution if a very large amount of waste heat would be connected to the grid. Further research on dynamic pricing should address several limitations of this study that were discussed in the Discussion section.

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Nomenclature

HFO	Heavy fuel oil
HOB	Heat only boiler
CHP	Combined heat and power
COP	Coefficient of performance
CO ₂	Carbon dioxide
DC	Data center
DH	District heating

LFO	Light fuel oil
PTES	Pit thermal energy storage
SDH	Solar district heating
TES	Thermal energy storage

Appendix A

Table A.1

Emission factors of different fuels in the case of Espoo

	CO ₂ Emission factor kg _{CO2} /MWh _{fuel}
Coal	341
HFO	284
LFO	267
Natural gas	198
Electricity	175
Biomass	0

Table A.2

Emission factors of different fuels in the case of Sønderborg [41].

	CO ₂ Emission factor kg _{CO2} /MWh _{fuel}
Waste	133
Natural gas	205
Electricity	304
Biomass	0

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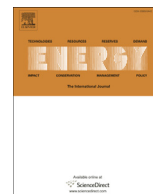
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Paper 9 – Modelling smart energy systems in tropical regions

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Modelling smart energy systems in tropical regions

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ABSTRACT

A large majority of energy systems models of smart urban energy systems are modelling moderate climate with seasonal variations, such as the European ones. The climate in the tropical region is dominated by very high stable temperatures and high humidity and lacks the moderate climate's seasonality. Furthermore, the smart energy system models tend to focus on CO₂ emissions only and lack integrated air pollution modelling of other air pollutants. In this study, an integrated urban energy system for a tropical climate was modelled, including modelling the interactions between power, cooling, gas, mobility and water desalination sectors. Five different large scale storages were modelled, too. The developed linear optimization model further included endogenous decisions about the share of district versus individual cooling, implementation of energy efficiency solutions and implementation of demand response measures in buildings and industry. Six scenarios for the year 2030 were developed in order to present a stepwise increase in energy system integration in a transition to a smart urban energy system in Singapore. The economically best performing scenario had 48% lower socio-economic costs, 68% lower CO_{2e} emissions, 15% higher particulate matter emissions and 2% larger primary energy consumption compared to a business-as-usual case.

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1. Introduction

Climate change has become one of the most important topics in political discussions among nations and cities around the world in recent years. Energy production and consumption are responsible for two-thirds of the world's greenhouse gas (GHG) emissions, making the energy sector one of the main contributors to the man-made climate change [1]. In order to tackle that problem, 195 countries worldwide signed the Paris agreement in 2015 [2]. The countries committed themselves to increase its efforts to cut CO_{2e} emissions with the aim of keeping the projected growth in global average temperature below 2 °C. An important part of those efforts is changing local and national energy systems from using fossil fuels towards using renewable energy sources (RES). Coastal cities are especially vulnerable to the climate change due to the sea level rise potential, stronger storms and other unexpected weather

events.

Cities will be among the major contributors in this transition process. Today, 54% of the world's population lives in cities and the United Nations forecasts that the share is expected to continuously grow, resulting in 66% of the world's population being urban in 2050 [3]. Cities are also facing the challenge of increasing energy consumption per capita, as urban energy use in the last 25 years has grown more than the urbanisation rate [4]. Cities can therefore easily become hotspots of air pollution, as they concentrate people, traffic, construction activity and energy use [5]. The World Health Organisation (WHO) states that more than 80% of the global urban population is exposed to air quality levels that are below WHO recommendations [6]. Particularly interesting in this context are cities in tropical climates. While heating demand accounts for a predominant part of the total energy consumption in moderate and cold climates, tropical climates are experiencing an ever growing cooling demand, as they are dominated by humid air and high temperatures throughout the year [7]. It is therefore important to analyse future energy systems in cities located in tropical climates, with a special emphasis on residential cooling.

Cooling systems have been the main focus in many research

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Nomenclature

abs_{DC}	Cold production for district cooling (DC) from single phase absorption units, MWh _c	MEC_{Sing}	Marginal external cost of air pollution in Singapore, €/ton
air_poll_j	Costs of air pollution emissions, €/kg	MEC_{UK}	Marginal external cost in the United Kingdom, €/ton
$air_poll_{inten,j}$	Air pollution intensity of a certain technology or energy within the system boundaries, kg/MWh	$methanol$	Methanol production via synthesis from syngas, MWh
B_y	Binary variable (0 or 1) used for modelling the choice of the refurbishment scenario	$petr_dem$	Gasoline demand, MWh
bio_cap	Maximum allowed biomass consumption in the modelled system, MWh	$petr_imp_k$	Price of import of gasoline in a specific hour, €/MWh
$chiller_{DC}$	Production of cold in DC from centralized electric chillers, MWh	RO	Fresh water production from sea water desalination using reverse osmosis (RO), m ³
$COP_{DC,chiller}$	Coefficient of performance of chillers in DC	$SOEC$	Hourly production of syngas from solid-oxide electrolyzers, MWh
$chiller_{individual}$	Production of cold from individual electric chillers, MWh	$SOFC$	Hourly production of electricity from solid-oxide fuel cells, MWh
$cool_{en,ef}$	Reduced cooling energy demand due to the increased energy efficiency, MWh	t	Hour, h
$cool_{demand,total}$	Total cooling demand, MWh	$var_O\&M_j$	Variable operating and maintenance costs of energy plants, €/MWh
$COP_{individual}$	Coefficient of performance of individual chillers	$water_{demand}$	Demand for fresh water production from sea desalination via RO, m ³
COP_{abs}	Coefficient of performance of absorbers	x_i	Capacity variables of energy plants and gas grid, MW
$CO2_cap$	Maximum amount of emissions allowed in the system, ton	x_j	Generation capacities of energy plants (8760 variables for each energy plant, representing the generation in each hour during the one year), MWh
$CO2_inten_j$	CO ₂ intensity of a certain technology or energy within the system boundaries, ton/MWh	$x_{j,EL}$	Hourly generation of technologies which generate electricity, MWh
$CO2_inten_k$	CO ₂ intensity of a certain technology or energy coming in or out of the system boundaries, ton/MWh	$x_{j,EL,biomass}$	Hourly generation of technologies which generate electricity and are driven by biomass, MWh
$CO2_j$	Costs of CO ₂ emissions, €/ton	$x_{j,EL,gas}$	Hourly generation of technologies which generate electricity and are driven by gas, MWh
DC_{demand}	DC demand, MWh	$x_{j,EL,other}$	Hourly generation of technologies which generate electricity and are driven by other fuel types, or are not fuel-driven (Photovoltaics (PVs) and wind turbines), MWh
dis_rate_i	Discount rate of the technology i , %	$x_{j,battery,storage_{ch}}$	Hourly charge of vehicles battery storage, MWh
el_dem	Electricity demand, MWh	$x_{j,battery,storage_dis}$	Hourly discharge of electricity of vehicles battery storage, MWh
ela	Elasticity of willingness to pay with respect to income	$x_{j,battery,storage_grid_dis,r}$	Hourly discharge of electricity of vehicles battery storage to the power grid (vehicle-to-grid (V2G)), MWh
$ele_{transport}$	Electricity demand for electrified part of the transport sector, MWh	$x_{j,grid,battery,storage_{ch}}$	Hourly charge of electricity grid battery storage, MWh
$fix_O\&M_i$	Fixed operating and maintenance costs of energy plants, €/MW	$x_{j,grid_battery,storage_dis}$	Hourly discharge of electricity grid battery storage, MWh
$flex$	Reduced electricity demand due to the load shifted in industry or buildings sector, MWh	$x_{j,heat,storage_ch,t}$	Hourly charge of heat to the heat storage operated in the district cooling (DC) system t , MWh
$flex_{ch}$	Additional demand for electricity due to the shifted load demand, MWh	$x_{j,heat,storage_dis,t}$	Hourly discharge of heat from the heat storage operated in the DH system t , MWh
$fuel_j$	Fuel cost of specific energy type, €/MWh _{fuel}	x_{j,an_dig}	Generation of gas after CO ₂ removal in anaerobic digester, MWh
gas_dem	Gas demand, MWh	$x_{j,wasteheat,l}$	Heat generation needed for absorption chillers; from gas, biomass, waste CHPs, solar thermal or waste heat from data centres, MWh
gas_imp_k	Price of import or export of gas in a specific hour, €/MWh	x_k	Import or export across the system boundaries of different types of energy (8760 variables per one type of energy, representing the flow in each hour during the one year), MWh
$gas_{synthesis}$	Synthetic natural gas production from syngas using gas synthesis, MWh	y	Chosen refurbishment scenario (out of several predefined ones), integer value
$geothermal_{DC}$	Cold production for DC from geothermal waste heat, MWh	Y_{Sing}	Gross national income per capita at purchasing power parity in Singapore, \$
$heat_level_r$	Heating energy content stored in the energy storage, MWh	Y_{UK}	Gross national income per capita at purchasing power parity in the United Kingdom, \$
$heat_dem_t$	Heat demand in district energy grid t , MWh	η_j	Efficiency of technology, MWh _{energy} /MWh _{fuel}
i	Energy technology index		
ind_cool_{demand}	Individual cooling demand, MWh		
inv_i	Total investment in technology i , €		
$inv_{en,ef,y}$	Investment cost of a certain building energy efficiency scenario, €		
j	Energy technologies that consume fuels and have emissions		
lev_inv_i	Levelized cost of investment over the energy plant lifetime, €/MW		
$lifetime_i$	Lifetime of the technology i , years		

papers. Bruelisauer et al. [7] analysed thermal properties of heat sinks and their effect on the performance of air-conditioning systems and showed that the temperature lift is particularly important for the performance of the overall cooling system in tropical climates like Singapore. With a focus on district cooling systems, the authors in Ref. [8] have emphasized how most of such systems are oversized, which leads to inefficient operation and overestimated investment costs. They developed a novel stochastic model for simulating cooling loads and applied it to a residential district in Wuhan, China. They found that oversimplified occupant behaviour assumptions caused overestimations of the peak and total cooling load. However, their model did not include system impacts of cooling loads on the whole energy system. Furthermore, Hoyo Arce et al. [9] developed a method for fast modelling of district heating and cooling networks, while a dynamic thermo-hydraulic model for district cooling networks was presented in Ref. [10]. The latter can be used for answering different economic and energy efficiency-related questions in design and operation of district cooling networks. However, both [9] and [10] focused solely on the district cooling sector and not on the overall energy system. B.W. Ang et al. [11] had the tropical and sub-tropical climate conditions as the main focus when they analysed how outdoor temperature increases affected electricity consumption in Singapore and Hong Kong. Their results showed that an average increase of 1 °C could cause a 3%–5% growth in total annual electricity consumption, due to increase in space cooling demand. Finally, Werner [12] provided an overview of the current situation of district heating and cooling systems in the world. His analysis revealed that around 67% of the global annual cooling demand came from the Middle East, where the average temperatures were much higher than in, for example, Europe or the United States. Moreover, he emphasized that future possibilities for larger-scale implementation of district cooling were promising; however, strong efforts were needed in order to realise them.

District cooling systems are especially beneficial when they are integrated with the distributed energy generation technologies, such as wind turbines or solar panels. Synergies between various energy generation and storage technologies with district heating or cooling networks can result in lower carbon emission, higher energy efficiency and reliability. While there are many studies focusing on the system integration in the regions where heating or both space heating and cooling are needed, the application and performance of district cooling integration for cooling dominated regions is still rarely investigated. One example of such integration for a small-scale area, namely a campus in Hong Kong has been carried out in Ref. [13]. Designed distributed energy system showed reduction in primary energy consumption and economic benefits due to the low operational costs. In Ref. [14], Hughes et al. investigated economic feasibility of combining desalination system with district cooling plants by utilizing waste heat recovery, demonstrating that the combination of the technologies is more cost effective than using the technologies independently. Moreover, utilization of intermittent renewable energy sources in district energy systems in hot-climates with a strong focus on exergetic analysis of ice storage was examined in Ref. [15]. Modelled scenarios included electricity generation, storage technologies and district cooling systems. However, the other parts of the energy system like transport sector and water desalination systems were not considered, revealing the gap in the current literature on smart urban energy systems in a hot climate.

In order to respond to increasing variability and uncertainty of demand due to the growing penetration of variable renewable energy technologies, future energy systems require high degree of system flexibility. Flexibility can be provided by a variety of options such as interventions in system operation, markets, load, network,

storages or through flexible generation [16]. A significant aspect of load interventions is demand response management (DSM). DSM has been especially well researched for operation of flexible consumption in residential sector where it can be used for various appliances, namely washing machines, dryers, dishwashers and electric hot water heaters [17]. A comprehensive review of DSM in variety of other sectors was given in Ref. [18]. The review showed considerable potential for flexibility in industry, commercial as well as households sector. However, the potential of DSM so far has not been modelled as a part of the overall energy system design.

Another important issue when modelling future energy systems is the inclusion of different externalities in the total costs of the system. These are mainly environmental costs and human-health related costs. When including the externalities from the urban energy system into the energy system modelling, most of the previous studies only took the greenhouse gas emissions into account. The air pollution was usually ignored [19]. Only a few studies considered the air pollution control aspects [20]. However, these studies used air pollution control element as model constraints and did not provide information about the external costs of the air pollution. Another example is the study in Ref. [21], where Zvingilaitė investigated human-health related externalities in an energy system modelling on the case of the Danish heat and power sectors. The main focus of the study was the energy production-related air pollution and the results showed that it was cheaper for the society to include externalities in the initial process of energy system planning than to pay for the resulting damages later. Thus, there is a research gap in terms of air pollution integrated holistic modelling in urban energy systems. In this study, the issue of air pollution was tackled by inclusion of the internalized external costs of the air pollution (NO_x, SO_x and particulate matter (PM) emissions) in the total socio-economic cost.

Nevertheless, this paper addresses the interplay between implementing energy efficiency measures in buildings, district energy share in the total thermal energy demand and renewable energy supply. The latter interplay was assessed in great detail in Ref. [22]; however, the assessment was carried out for European countries, dominated by distinct seasons throughout the year. The interplay being assessed in this paper focuses on the tropical climates, dominated by lack of seasonality in demand, with majority of thermal energy demand being in the form of cooling demand.

The presented literature review shows that there is a lack of systematic research on cooling integration into energy systems in hot and humid climates. Smart energy systems [23], including smart district heating systems, have been the topic of research for many different use cases, whereas, there is a lack of research on the potential of district cooling integration with other energy sectors constituting smart energy system. Furthermore, concerning the best of knowledge of the authors, there is no research dealing with the integration of district cooling into smart energy systems and future smart energy cities in tropical regions.

In order to improve the state-of-the art of the energy planning in the tropical climates, this paper brings the following novelties:

- Integrated, holistic urban energy modelling has been applied to the tropical climate, dominated by the lack of distinct seasonality, having steady cooling demand, as well as solar insolation throughout the year. The integrated urban energy systems in this paper included power, cooling, gas, mobility and water desalination sectors.
- Air pollution has been endogenously modelled and different sources of air pollution have been tackled. The air pollution costs were internalized in the overall socio-economic costs.
- The interplay between energy supply, district (cooling) energy supply and energy efficiency has been endogenously modelled,

meaning that neither of the shares was predefined by a modeller.

- Flexible demand of industry and buildings has been also endogenously modelled, having as a consequence the possibility that the model result selects the optimal mix of solutions in the complex urban environment.
- A comparison between the energy systems of a city seeking for the self-sustainability and when it also utilizes the energy from its surroundings has been carried out.

Thus, the aim of this paper is to assess whether the district cooling (DC) adoption in hot and humid climates is socio-economically feasible on the system scale and whether it can serve as an integration point for intermittent renewable energy sources. Moreover, the aim of the developed model is to find the optimal mix between the renewable energy supply, district cooling and building energy efficiency. Finally, the air pollution and external costs those emissions are imposing on the society have been calculated and put into the CO₂ emissions agenda perspective.

This paper is organized as follows, in the Methods section, a flow chart of the model is presented in order to make it clearer what is the model being used here capable of modelling. Moreover, the most important equations of the optimization model are presented here, while the complete optimization model is presented in [Appendix B](#). The case study that was used to represent a hot climate is presented in the Case study and scenario development section. Further section presents the most important results, showing the interplay between different energy sectors, primary energy savings, air pollution impact and GHG emissions of different scenarios. The paper ends with a discussion of the results, outlook of the future research and main conclusions of this paper.

2. Methods

The smart energy system was modelled taking electricity, cooling, water desalination, gas and mobility sectors into account. A linear mixed-integer optimization model was developed using Gurobi solver and Matlab interface. Integer variables were constrained to binary ones only.

The optimization model used in this paper is a significantly expanded version of the model that was previously developed in Ref. [24], and expanded in Ref. [25]. The model was improved by adding endogenous decisions on the share of DC versus individual cooling, selecting energy efficiency strategy in buildings and implementing DSM in industry and households. It was further improved by adding N₂O and CH₄ gases to the CO₂, in order to better represent GHG emissions, and modelling the air pollution. Throughout this paper, N₂O, CH₄ and CO₂ emissions are jointly reported as CO_{2e} emissions. The flow chart of the optimization model can be seen in [Fig. 1](#). This section follows with the explanation of the most important equations of the optimization model, while the representation of all the equations of the optimization model can be found in [Appendix B](#).

2.1. Objective function and variables

The goal of the optimization was to minimize the total socio-economic costs, as shown in eq. (1). The total socio-economic costs included levelized costs of investment over the lifetime of the energy plant, storages, smart controls for load shifting and energy refurbishment of buildings, fixed and variable operating and maintenance (O&M) costs, fuel costs, CO₂ costs, costs of other greenhouse gases (N₂O and CH₄) and costs of air pollution. CO_{2e} emissions were calculated using the production methodology, which meant that all the emissions within the system boundaries

were taken into account, no matter whether the products were consumed locally or exported. The linear mixed integer optimization model developed in this paper is an updated version of the model presented in Ref. [24]. A detailed description of the variables and the corresponding units can be found in Nomenclature section. Only an excerpt from the whole model is presented in this section. All the equations of the developed optimization model can be found in [Appendix B](#).

$$\begin{aligned} \min Z = & \sum_{i=1}^n (fix_O\&M_i + lev_{inv\ i})x_i + \sum_{j=1}^m \left(var_O\&M_j + \frac{fuel_j}{\eta_j} \right. \\ & \left. + CO2e_j \cdot CO2e_{inten\ j} + air_poll_j \cdot air_poll_{inten\ j} \right) x_j \\ & + \sum_{k=1}^p (gas_imp_exp_k + petr_imp_k)x_k + \sum_{l=1}^y inv_{en,ef\ y} \cdot B_y \end{aligned} \quad (1)$$

As an example, the inequality constraint of the power balance is shown by eq. (2). The electricity demand could be met by gas combined heat and power plant (CHP), biomass CHP, waste CHP, photovoltaics (PVs), wind turbines, solid-oxide fuel cells (SOFC) or from the battery storage (2). Additional electricity demand could be imposed from individual electric chillers, DC electric chillers, pumping needs for geothermal DC, reverse osmosis, electrified transport or charging the battery storage (2).

$$\begin{aligned} x_{j,EL,gas} + x_{j,EL,biomass} + x_{j,EL,other} + x_{j,battery_storage_grid_dis} \\ + x_{j,grid_battery_storage_dis} + SOFC - x_{j,battery_storage_ch} \\ - x_{j,grid_battery_storage_ch} \cdot \frac{chiller_{DC}}{COP_{DC_chiller}} - \frac{chiller_{individual}}{COP_{individual}} \\ - 0.1 \cdot geothermal_{DC} - RO - \frac{SOEC}{\eta_{SOEC}} + flex - flex_{ch} \\ \geq el_dem \end{aligned} \quad (2)$$

One of the implemented environmental constraints in the model was the maximum allowed CO_{2e} emissions, as shown by eq. (3).

$$CO2e_{inten\ j} \cdot x_j + CO2e_{inten\ k} \cdot x_{petrol} \leq CO2_{cap} \quad (3)$$

2.2. External costs of air pollution

The calculation of regional-specific estimation of the air pollution external costs was based on data collected from the literature. This simplified approach was suitable since the purpose of the external costs was primarily to demonstrate their importance for the overall energy system modelling. For detailed analysis such calculation would require resource intensive impact pathway approach [26]. The data of energy external costs for Singapore were converted from the marginal external cost data for the United Kingdom [27], using the value transfer approach, as shown in eq. (4).

$$air_poll_j = MEC_{UK} \times \left(\frac{Y_{Sing}}{Y_{UK}} \right)^{ela} \quad (4)$$

Values for variables Y_{Sing} and Y_{UK} were obtained from The World Bank data [28] while the value of 0.32 for ela was directly adopted from the research on estimation of the health impact costs for particle pollution in Singapore [29].

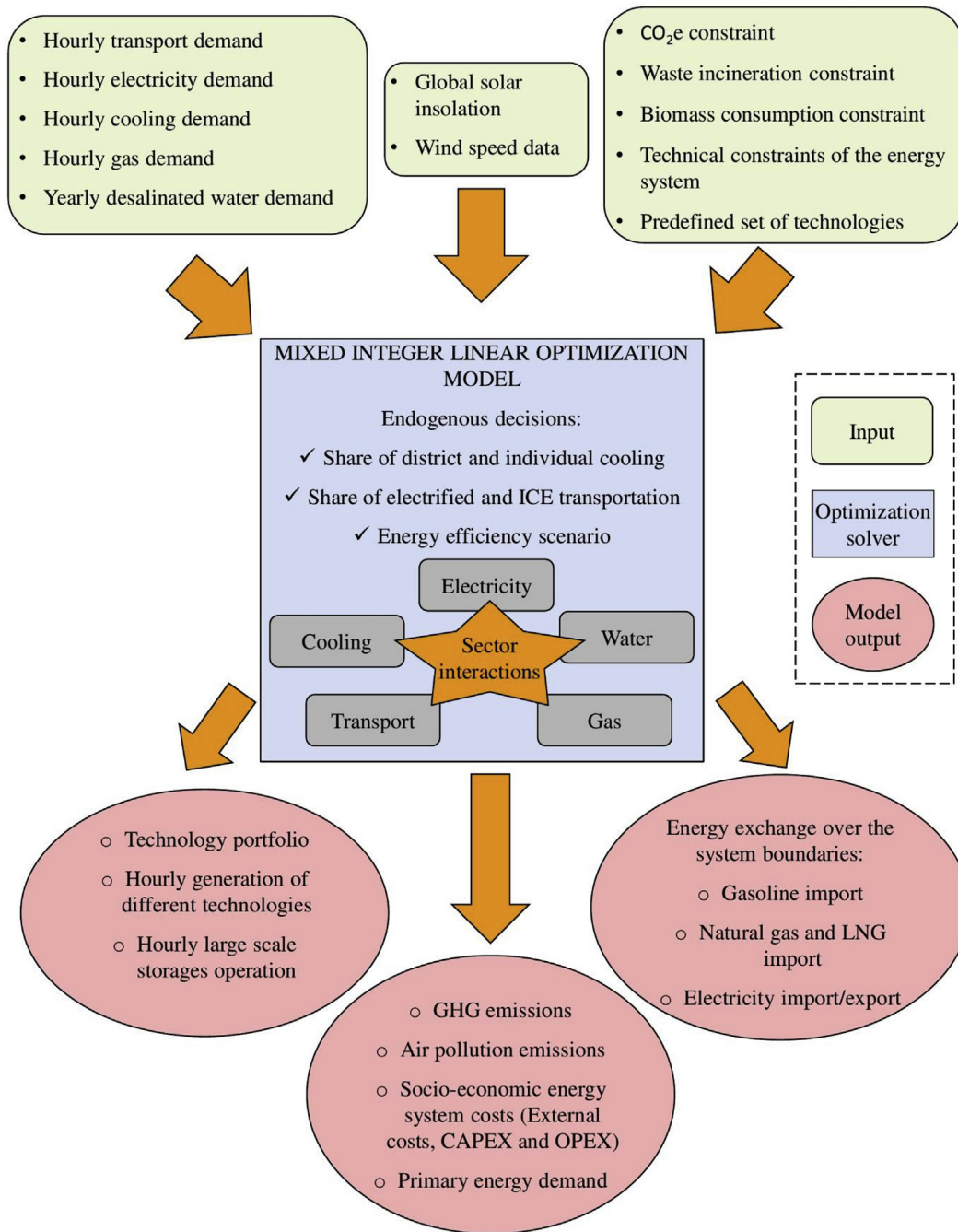


Fig. 1. A flow chart of the optimization model used for the energy system planning.

2.3. Case study and scenario development

Singapore was chosen for the case study as it is a country that also represents a city, at a high level of economic development and suitable for district cooling research, as it is located very close to the equator.

CO₂e emissions factors, capacities of energy facilities, energy demand and the description of transportation sector can be found in great detail in Refs. [30] and [31]. Global warming potential of CH₄ and N₂O used in this case study were equivalent to 24 and 298 times CO₂, respectively.

Singapore is currently rolling in a carbon tax scheme, which taxes CO₂e emissions at fixed rate. The proposed carbon tax, which

is anticipated starting from the year 2019, is estimated between 10 and 20 SGD [32]. The projected price for the year 2030 used in this study was 35 SGD (21.6 EUR), in line with the expected relative increase of the price of the CO₂ allowance in the European Union [33].

Air pollution factors that were used in the model are presented in Table 1.

Marginal external costs for air pollution can be seen in Table 2. Costs differ according to the pollutant type and source of the pollution. The latter is divided into two groups, stationary such as energy plants and non-stationary sources such as transport sector.

Different levels of marginal cost values, i.e. low, high and medium were calculated to tackle the issue of the limitation that arises

Table 1

Emissions of air pollutants from different technologies and fuels in the years 2015 and 2030 (references refer to the entire row unless otherwise stated in a specific cell).

(g/GJ)	2015					2030					Ref
	NO _x	SO _x	CH ₄	N ₂ O	PM	NO _x	SO _x	CH ₄	N ₂ O	PM	
Gas boiler	10–13	0	3	1	0,1 [34]	8–11	0	3	1	0,1 [34]	[35]
Gas CHP	48	0	1,5	1	0,05 [34]	42	0	1,5	1	0,05 [34]	[35]
Biomass boiler	81	1,9	0	0,8	10 [34]	81	1,9	0	0,8	10 [34]	[35]
Biomass CHP	81	1,9	0	0,8	4,82 [34]	81	1,9	0	0,8	4,82 [34]	[35]
Waste CHP	124	0	0,59	1,2	0,29 [34]	30	0	0,59	1,2	0,29 [34]	[35]
Gasoline	187	0	7	18	1,72 [36]	187	0	7	18	1,72 [36]	[37]
Methanol	29,915	0	0	0	0	6,94	0	0	0	0	[38]

Table 2

Marginal external costs in Singapore for 2015, point and non-point sources of pollution €/ton.

Air pollution	Sector	Low	High	Medium	Ref
NO _x	Energy generation (Point)	735	2943	1839	[27]
	Transport (Non-point)	14,708	58,838	36,774	[27]
SO _x	Energy generation (Point)	2762	3887	3419	[27]
	Transport (Non-point)	7549	11,324	9933	[39]
PM	Energy generation (Point)	3977	5772	5077	[27]
	Transport (Non-point)	79,527	115,424	101,572	[27]

* Adjusting damage cost value over time accounting for 2% uplift is taken into account for the implementation of the values in the model [27].

from different valuation of health and environment. The valuation is specific to location and culture and therefore it may limit the reliability of the value transfer approach. For the purpose of this paper, the medium value of marginal external costs value was selected as the input for the optimization model, in order to follow the approach that was taken in the previous research [40]. Moreover, in order to check the extreme cases of the air pollution socio-economic impact, a sensitivity analysis was carried out with the low and high air pollution cost levels. The results of the sensitivity analysis have been discussed in the Discussion section.

Both air pollution costs and environmental costs (CO₂e emissions) were internalized in the model. By taking the latter approach, a recommendation from the Oxford Institute for Energy Studies was followed, claiming that the energy modelling should be technology neutral after internalizing environmental externalities [41].

Most of the economic and technical data for the predefined technologies were obtained from the technology datasheet published by Energinet.dk, the Danish transmission system operator [42]. Moreover, an overview of the investment costs, as well as fixed and variable operating and maintenance costs for most of the technologies predefined in this model can be seen in Ref. [24]. The techno-economic data used for reversible osmosis technology was obtained from Ref. [43]. There are two main absorption chillers technologies, LiBr-water and water-ammonia ones. A detailed overview of absorption technologies, technical constraints, investment costs and expected development can be found in Ref. [44]. A single effect LiBr-water absorption technology for DC was assumed in this paper. Assumed thermal COP of those chillers was 0.7, at heat source temperature between 90 and 95 °C [23]. The typical capacity of a single unit single-effect LiBr-water absorption chillers is 5–7000 kW and it is typically used for cooling in industry and large-scale district cooling [44]. The investment cost of large scale LiBr-water absorption chillers used in this study was 120,000 €/MW_c [24].

2.4. Scenarios validation

In order to ensure that the model was performing well, the

business as usual (BAU) scenario was validated against the projection of the energy system modelled in EnergyPLAN [31]. The main indicators of scenario validation are summarized in Table 3. It can be seen that the BAU scenario can be validated against the EnergyPLAN model.

A relatively large difference of 6.9% is still tolerable keeping in mind the statistical uncertainties about the future projections of the BAU scenario.

In order to validate the assumption used to calculate the external costs of the air pollution, the results for Singapore were validated against the air pollution external costs of a country with similar population, i.e. Norway. The economic cost due to the health issues caused by air pollution in Norway was 700 million EUR (calculated from 2010 USD) [45]. The negative externality due to air pollution in Singapore was calculated to be 682 million EUR in the BAU case and the result can be seen in Table 8. Emissions of CO₂e, pollutants and particles and respective socio economic costs of them. Hence, the calculated air pollution caused externality can be considered as validated.

2.5. Analysis of the scenarios

The scenarios developed in this paper represent a stepwise integration of renewable energy based technologies, each step representing a higher degree of systems integration and for the Scenarios 6 and 7 additional CO₂e limitation. Scenarios 2 to 6 were modelled with constraints for PV and the solar thermal capacity due to the space availability, while only the Scenario 7 was left without such constraints. This was done in order to show the impact of seeking for self-sustainability within the city (Scenario 2–6) versus utilizing the energy outside from the city borders (Scenario 7). A detailed representation of scenarios can be seen in Table 4. All scenarios were developed for the energy system anticipated in the year 2030.

The scenarios were developed in this specific order in order to detect the system impact of integration of specific energy sector and/or technologies. Furthermore, the developed optimization model is suitable for analysing complex interactions between different energy sectors. Specific technologies that integrated different sectors in this case study were: electric chillers in district cooling, waste heat from power plants as an input for absorption chillers, reversible osmosis for desalination of water, solid oxide electrolyzer cell (SOEC) and SOFC and vehicles to grid technology. Furthermore, no less than five different storage technologies were modelled in this case study, as shown in Table 9.

The scenarios differed according to the combination of introduced energy technologies where the last two scenarios were additionally constrained with the limitation on CO₂e emissions. The additional CO₂e constraint corresponds to the 40% reduction in CO₂e emissions compared to the 1990 level. The latter assumption was implemented in order to assess the costs of implementing policy similar to that of the European Union, although its

Table 3

Comparison of the results in the current model and the projections modelled in EnergyPLAN simulation software for the year 2030.

	Projection from reference [31] (TWh)	Scenario 1 BAU (TWh) (This study)	Difference
CO ₂ emissions	50.7	49.1	3.3%
PES	223.7	208.3	6.9%

Table 4Representation of scenarios according to the implemented technologies or CO₂e emission limitation (all scenarios developed for the year 2030).

Technologies/constraints	Scenario 1 BAU	Scenario 2 DC	Scenario 3 DC- PV	Scenario 4 DC-PV- el.transp.	Scenario 5 DSM- EnEff	Scenario 6 CO ₂	Scenario 7 non self- sufficient
Transport Electrification	✓ ^a	✓ ^a	✓ ^a	✓	✓	✓	✓
Photovoltaics	✓ ^b	✓ ^b	✓	✓	✓	✓	✓ ^d
District Cooling		✓	✓	✓	✓	✓	✓
SOFC, SOEC, synthetic fuels				✓	✓	✓	✓
DSM and buildings energy efficiency					✓	✓	✓
CO ₂ e emissions						✓ ^c	✓ ^c

^a Maximum 10% of gasoline demand shifted to electrified transport (other scenarios did not have an upper limit on transport electrification rate).^b Maximum installed capacity of PVs equal to 1000 MW.^c CO₂e emissions constrained to 13.1 Mt which is equal to 40% reduction of CO₂e emissions in 2030 compared to 1990 level.^d PV and solar thermal not constrained. This scenario represents the city that receives a portion of energy, generated from PVs and solar thermal energy, which are located outside of the city.

environmental policy is stricter than the current Singapore's goals.

For each scenario, the impact on energy supply, the economy and the environment was assessed. The impact on the energy supply was represented as primary energy supply (PES, equal to the primary energy demand). For the economic indicator, the total annual socio-economic cost of the energy system was calculated. Even though the contribution of indicators related to job creation is recognised to be beneficial in smart energy systems [46], it remained out of the scope of this paper. Environmental impact was estimated on the basis of four different indicators given as emissions of air polluting gases (NO_x and SO_x), greenhouse gases (CH₄, N₂O and CO₂, reported as CO₂e) and PM as shown in Table 1.

The model presented here has the capability of modelling all four flexibility sources in the energy system, i.e. electricity import/export over the system boundaries, power-to-heat and power-to-gas, energy storage and demand response in industry and households. However, for this specific case study electricity import/export was not allowed, due to the current energy security policy of Singapore. The other three flexibility sources were modelled for this specific case study. The potential error caused by not implementing the electricity import/export possibility over the city borders as another source of flexibility was assessed by carrying out a sensitivity analysis, results of which have been presented and discussed in the Discussion section.

The demand side management was introduced for industry and household sectors. The variables that were used in the model can be seen in Table 5. The load management factor is defined as the share of the displaceable power at the overall power demand of a particular application. The factor includes both technical

limitations arising from the process, as well as technical limitations arising from different uses.

The description of energy efficiency measures can be found in Ref. [49]. Energy efficiency options A, B, C and D, that can be found in Ref. [49], were predefined in the optimization model and denoted as energy efficiency options A to D, as shown in Table 6. Measures are divided into 4 options according to the percentage of resulting electricity savings and costs arising from the implementation of each option. Table 6 represents the main indicators which were used in the model to select the best energy efficiency scenario.

Capital costs were modelled using binary variables denoting existing/non-existing investment. The latter means that if the model chose to invest in a certain energy efficiency option, the whole investment amount for the whole year of energy savings would occur in the model. It was not possible to achieve savings only in certain hours of the year, as majority of the investment costs for increased energy efficiency are fixed ones.

2.6. Specific constraints for the case of Singapore

There were several specific constraints that were implemented for the case of the city of Singapore. First, in scenarios 3–6, the PV capacity was constrained to 9450 MW, which can be installed on all the rooftops throughout the city [50]. In scenarios 1–6, the solar thermal capacity was constrained to 1700 MW, which represents 0.5% of the land area in the city. Only the last scenario (non self-sufficient) allowed for unconstrained installation of PV and solar thermal technology. In reality, the latter would mean that those

Table 5

Demand side management values for industry and households.

Sector	Load management factor (%)	Max duration (h)	Frequency of the activation in a year	Price (EUR/MW)
Industry				
Chemical industry [18]	30	4	40	87,318 [47]
Petroleum refining [47]	15	4	n/a	87,318 [47]
Households				
Water heater [18]	25	2	220	20,075 [48]
Refrigerator and freezer [18]	33	2 ^a	365	15,400 [48]

^a The value is modified according to the assumption that modern appliances are suitable for longer load shifting duration than stated in the reference.

Table 6
Indicators of different energy efficiency scenarios for buildings.

Energy efficiency options	Electricity savings (%)	Capital cost per savings (EUR/MWh)
A	0	—
B	4.60%	15.6
C	22.30%	5.3
D	28.40%	61.4

installations would need to be installed outside of the city borders. However, it was useful scenario for evaluation of potential socio-economic costs and air pollution when focusing on self-sustainability versus allowing the energy system of a city to be integrated with the surrounding area.

Geothermal energy was constrained to 400 MW_{th}, as this was the amount of geothermal potential found in the literature [51]. Waste incineration plant was narrowly constrained so that it could incinerate only the waste generated in the area. The latter approach led to the possible capacity of waste CHP plant from 161 MW to 170 MW, with steady operation throughout the year.

Singapore does not have a potential for significant amounts of sustainable biomass to be utilized in the CHP plant. Hence, it was assumed that all the biomass that was needed for the operation of biomass CHP originated from sea algae, increasing the overall cost of the energy system.

Nevertheless, on average, 200 million gallons a day of desalinated water needed to be produced via reversible osmosis, in line with the envisaged policy for the year 2030 [52].

3. Results

This section presents the results and the following analyses of seven different scenarios for the energy system of Singapore. It is important to note that the evaluation of the air pollution emissions in this section does not include air pollutant emissions from the industrial energy consumption, and related internalized external costs of air pollution from the industry. Furthermore, the total energy consumption in the industrial sector was not optimized inside the optimization model due to the lack of available data. They were considered to be fixed, i.e. yearly rise in the industry energy consumption due to the economic growth, is expected to be cancelled out with the energy efficiency measures that will be undertaken in the industry [53], keeping primary energy consumption and emissions in the industrial sector flat. The only assumed change was that by the year 2030 the oil consumption of the industry will be replaced with natural gas (or liquefied natural gas) consumption.

Primary energy supply displayed in Fig. 3 was an important indicator for the energy system evaluation, as it shows the integration level of RES. Higher RES penetration level is supported by synergies between different energy sectors, i.e. power system, cooling sector, gas grid and transport sector. The lowest PES value occurred in Scenario 5 (DSM-EnEff) and it was 20% lower than the value in the BAU scenario. Fossil fuel supply was the lowest in scenarios 6 and 7, in which it represented 34% and 30% of the total primary energy supply, respectively.

Several issues concerning Fig. 3 need to be clarified. First, one can note that scenarios 2–5 have stepwise reductions in PES compared to the BAU scenario. There were several reasons for those energy savings. First, district cooling helped utilizing waste heat from waste incineration, biomass and gas CHP plants. Second, electrification of the transport significantly increased its efficiency as electric vehicles have approximately three times better efficiency compared to the gasoline vehicles [54]. Third, energy efficiency scenario C from Table 6, adopted in scenarios 5–7, reduced cooling

energy demand for 22.3%, which can be seen in Fig. 2.

It can be further noted from Fig. 3 that in scenarios 6 and 7, although they have the lowest fossil fuel supply, their PES is higher than in other scenarios. In scenario 6, the main reason is that due to the CO₂e constraint, 64% of final energy demand for electricity was met from biomass CHPs, which had lower electrical efficiency compared to the gas CHPs, 29% compared to 50%. The latter caused larger demand for PES. In scenario 7, one part of increased PES originated from the higher biomass demand than in scenario 1–5, as 11% of final electricity demand is met by biomass CHP. More important reason is that the scenario 7 had the largest share of DC out of all scenarios, as 98% of the total cooling demand was met by DC, which can be seen from Fig. 2. DC mostly utilized low grade heat via absorber units, and most of this heat was generated by solar thermal units. Although this renewable heat is cheap from the socio-economic point of view, absorption units had COP of only 0.7 and thus, the demand for PES was relatively high. On the other hand, meeting cooling energy demand via individual cooling in other scenarios was met by individual electric chillers with COP value of 3. As in scenarios 2–5 most of electricity was generated by gas CHPs with electrical efficiency of 50%, the resulting PES was lower than in scenario 7. Moreover, PES in scenario 7 was only 2.4% larger than in BAU scenario.

It is interesting to observe the optimal shares of district cooling, one of the endogenous decisions of the optimization model in Fig. 2. The optimal share of DC in scenarios 2–5 was between 37% and 47%. As some of the constraints imposed in the model were capacities of solar thermal and geothermal energy, due to the space availability and geothermal potential, there was not enough of cheap heat available in the system. Hence, for the part of the cooling demand that could not be satisfied via available cheap heat from geothermal, solar thermal or CHP plants and absorption units, it was more efficient to satisfy the cooling demand using electricity driven individual chillers with COP value of 3. Only in the last two scenarios DC shares increased significantly, to 76% and 98%,

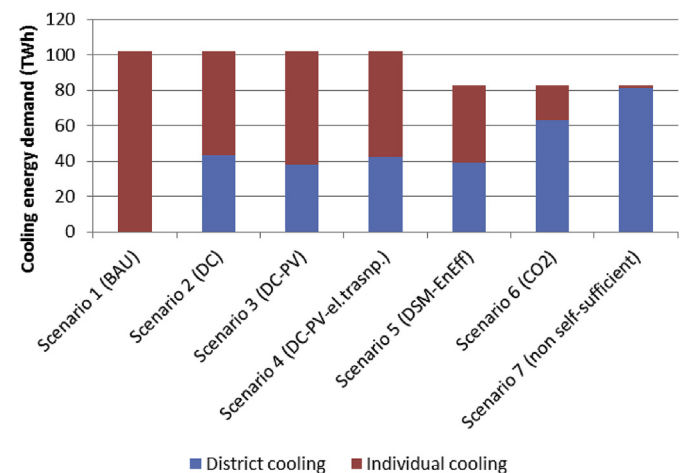


Fig. 2. District cooling versus individual cooling share in different scenarios.

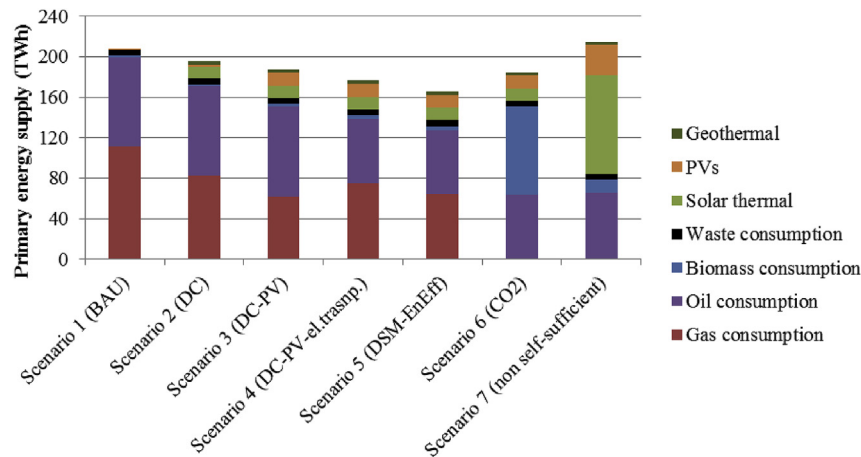


Fig. 3. Primary energy supply by fuel (63.4 TWh of oil supply in scenarios 1 to 5 belongs to industry, which was not optimized within the model. 63.4 TWh of gas supply in scenarios 6 and 7 belongs to industry sector).

respectively. For the scenario 6, the reason was that there was more available heat from biomass CHP units, which were erected instead of gas CHPs, in order to meet the tight CO₂e constraint. As biomass CHP had lower electrical efficiency compared to the gas CHPs, consequently it generated more heat per unit of electricity generated than the gas CHP. In the Scenario 7, as there was no constraint on the capacity of solar thermal capacity, this was the cheapest option to produce heat which fed absorption units to produce cold for meeting cooling energy demand.

It is interesting to observe changes in electricity generation in different scenarios according to the share of the specific generation source as shown in Fig. 4 and according to the real values of the generated electricity as shown in Table 7. Constraints imposed on the CO₂e emissions in Scenario 6 (CO₂ scenario) resulted in biomass substituting natural gas for energy production. The latter resulted in the biomass CHP share in electricity generation of 64% in Scenario 6 (CO₂ scenario). As Singapore had no sustainable biomass sources, all the biomass originated from sea algae production making the energy system more expensive. In scenario 7, the one

which did not have a cap on PV capacity, it was shown that it is optimal to meet a significant 80% of final electricity demand by photovoltaics. Two main reasons are that it correlates the cooling energy demand, as well as the steady solar irradiation throughout the whole year as Singapore does not have distinct seasons during the year. Scenario 7 also had 434 MW of installed SOFC, as well as 1826 MW of SOEC, which served as a source of flexibility in the system with a large share of PV electricity generation. Furthermore, another technology that fostered integration of significant share of PV generation in the system was centralized electric chillers, used for district cooling supply. In scenario 7, absorbers in DC system had the capacity of 11,187 MW, while centralized electric chillers had the capacity of 1258 MW_{th} (COP = 5).

In Table 8, selected emissions are summarized indicating that higher share of DC, RES and the integration of different sectors resulted in lower CO₂e emissions. It is worth noting here that 13.1 Mt of CO₂e emissions, out of the total reported emissions in Table 8, originated from the industrial consumption, which was not optimized inside the model. Opposite to this declining trend for CO₂

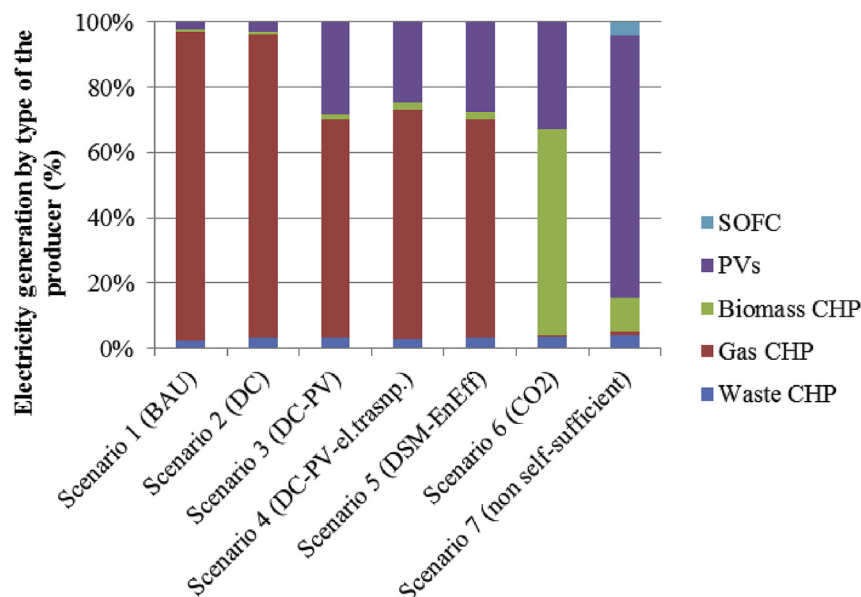


Fig. 4. Shares of electricity generation sources by type.

Table 7

Mix of electricity generation sources (TWh).

	Scenario 1 BAU	Scenario 2 DC	Scenario 3 DC-PV	Scenario 4 DC-PV-el.transp.	Scenario 5 DSM-EnEff	Scenario 6 CO ₂	Scenario 7 non self-sufficient
Waste CHP	1.41	1.49	1.49	1.49	1.49	1.49	1.41
Gas CHP	55.48	41.15	31.01	37.42	32.10	0.02	0.47
Biomass CHP	0.33	0.35	0.64	1.09	1.04	25.23	3.81
PVs	1.39	1.39	13.04	13.11	13.10	12.99	29.54
SOFC	0.00	0.00	0.00	0.00	0.00	0.00	1.50
Total	58.62	44.38	46.19	53.11	47.73	39.74	36.74

Table 8Emissions of CO₂e, pollutants and particles and respective socio economic costs of them.

	Scenario 1 BAU	Scenario 2 DC	Scenario 3 DC-PV	Scenario 4 DC-PV-el.transp.	Scenario 5 DSM-EnEff	Scenario 6 CO ₂	Scenario 7 non self-sufficient
NOx (t)	34,957	30,676	27,902	13,245	11,571	26,177	4612
SOx (kg)	7874	8311	15,168	25,755	24,542	595,024	89,864
PM (kg)	204,358	200,651	214,396	86,778	81,651	1,517,194	234,308
CO ₂ e (Mt)	44	38	34	29	27	14	14
Socio-economic cost: air pollution (mil €)	682	674	669	31	27	63	10
Socio-economic cost: CO ₂ e emissions (mil €)	910	787	700	614	568	292	294

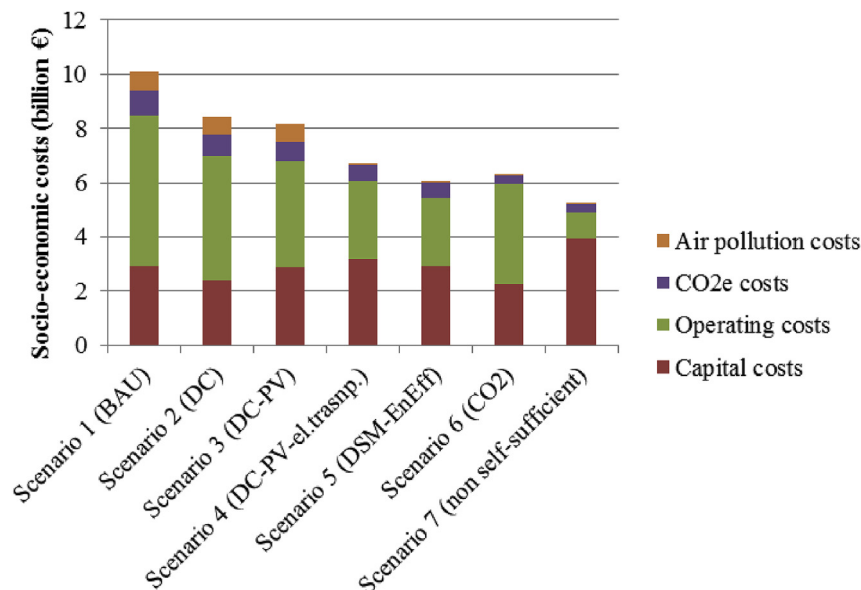
emissions, air pollution trend was not so straightforward and its values varied across different scenarios. The scenario with a constraint on CO₂e emissions (CO₂ scenario) had PM emissions 7.4 times higher than in the BAU scenario. NOx emissions followed declining trend except in the case where CO₂e was limited.

It can be further noted from Table 8 that although air pollution emissions in Scenario 6 were much larger than in scenarios 1 to 3, the resulting socio-economic cost was much lower. The reason is that the majority of the air pollution emissions in Scenario 6 originated from biomass CHP plants, which represented the point-source pollutant, which can be better handled than the non-point source pollutants. On the other hand, in scenarios 1 to 3, the majority of emissions originated from gasoline use in vehicles, which represent the non-point source of pollution, for which health externalities are much costlier than for the point source pollutants.

The total socio-economic costs of Scenarios 2–7 were 16%–48%

lower than in the BAU scenario as shown in Fig. 5. Scenario 6 (CO₂ scenario) did not follow the same decreasing trend and it had costs higher than Scenario 4 (DC-PV-el.transp.) and Scenario 5 (DSM-EnEff), still 37% lower than BAU scenario. The increased costs in Scenario 6, compared to the scenarios 4 and 5, showed that tight constraints on the CO₂e emissions can result in a slightly higher socio-cost, although the carbon tax was already accounted for in the reported socio-economic costs. On the other hand, Scenario 7 shows that not seeking for self-sustainability of cities, but rather also utilizing the resources from the surroundings, can bring the costs down, in line with the increase in the penetration of renewable energy sources and decreased carbon and air pollution emissions.

Fig. 6 represents hourly electricity generation mix on the chosen days in Scenario 5 (DSM-EnEff). One can note that the shifted load (Flexible demand utilized industry and Flexible demand utilized

**Fig. 5.** The total socio-economic costs in different scenarios.

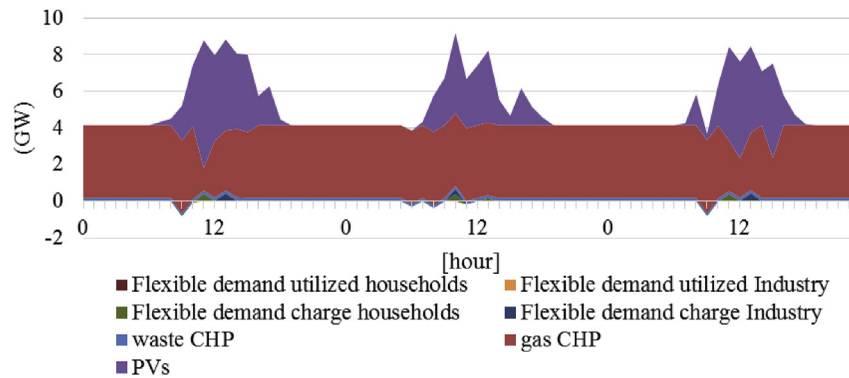


Fig. 6. Hourly electricity generation mix in DSM-EnEff (Scenario 5) from the 07th to the 09th of July.

households) occurred just before the peak PV generation. Although usually the role of DSM is to reduce the peak demand, in this case peak demand was actually increased due to the flexible demand. The reason was that the peak demand closely matched the increased PV generation. Waste CHP had constant generation due to the constraints of consuming all the supplied waste. Outside the PV generation periods, most of the demand was met by gas CHPs.

3.1. Usage of different storages

Different storage solutions were modelled and the optimal capacities of different storage types is shown in Table 9. The detailed hourly operation of different storage types can be found in Appendix A.

In the DC sector, PTES storage was used and it stored heat at 95 °C, before utilizing it in absorption units. It was more efficient, more energy dense (lower space demand) and cheaper solution than using cold (ice) storage which would store the cold generated in the absorption units. Grid battery storage was only needed in the BAU scenario, where no DC was implemented and in the Scenario 7 (non self-sufficient), in which the share of intermittent PV generation reached 80% of the final electricity demand. The largest capacity of PTES storage occurred in the Scenario 7, the one with the largest installed capacity of solar thermal.

Syngas (hydrogen) storage, together with SOFC and SOEC only occurred in the Scenario 7, as it increased the flexibility in the energy system with large share of electricity demand met by variable renewable energy generation.

Gas storage started to be feasible in scenarios that had significant share of installed PV capacity, as in those scenarios gas CHP units needed to operate more flexibly, due to the larger share of variable PV generation. In scenarios 6 and 7, gas storage was not feasible as the gas demand was very low.

Finally, one can note that together with the electrification of the transport sector, there is an important role of EV batteries, not only for the vehicles, but for the grid flexibility, too, as vehicle-to-grid

possibility was utilized in scenarios 4–7. The discharge of batteries to the distribution grid amounted to 3.3% of the total EV batteries utilization in scenarios 4 and 5, 1.1% in Scenario 6 and 15.5% in Scenario 7. The discharge of batteries to the grid in scenario 1–3 was 7.8%, 23.6% and 129.3% of the total electricity demand in the transport sector in those scenarios. Relatively large vehicle-to-grid utilization in the Scenario 3 was caused by large share of PV variable generation and still not widely electrified transport sector (only 10% of transport sector was electrified in the Scenario 3).

Although the installed capacity of EV batteries in absolute terms in scenarios 1–3 was much lower than in scenarios 4–7, its relative utilization was much larger.

It can be seen that the significant share of variable PV generation in Scenario 7 was absorbed by the combination of increased size of thermal energy storage, demand side management of industry and buildings, hydrogen technology (SOFC, SOEC and syngas storage), grid battery storage and increased vehicle-to-grid utilization of EV batteries.

4. Discussion

The main goal of this paper was to assess whether district cooling adoption in hot and humid climates would be socio-economically feasible at the system scale and whether it could serve to integrate more intermittent renewable energy sources than in the business as usual case. Another aim of the developed model was to find the optimal mix between the renewable energy supply, district cooling and building energy efficiency. Both of the goals were successfully achieved by integrating district cooling, along with other flexible technologies, into the smart energy system. In all the scenarios (2–7) in which district cooling penetration was between 37% and 98%. The DC share was the largest in the Scenario 7, in which the cheap thermal energy from solar thermal was unconstrained in capacity, as well as the capacity of variable PV generation in the power sector. DC was important integration step as it utilized heat available from waste, gas and biomass CHP units,

Table 9
Total capacities of different storage types (GWh)

	Scenario 1 BAU	Scenario 2 DC	Scenario 3 DC- PV	Scenario 4 DC-PV- el.transp.	Scenario 5 DSM- EnEff	Scenario 6 CO ₂	Scenario 7 non self- sufficient
Pit Thermal Energy Storage (PTES)	0	153	297	163	151	96	492
Grid battery storage	5.9	0	0	0	0	0	20.6
Syngas storage	0	0	0	0	0	0	222.7
Gas storage	7.2	0	24.8	21.8	20.9	0	0
EV battery	1.0	1.5	4.9	15.1	15.0	14.9	23.3

geothermal and solar thermal energy.

Comparing scenarios 2–7 with scenario 1 (BAU), one can note that significant PES savings were achieved by the integration of DC. The reason was that DC was able to utilize waste heat from gas and biomass CHP plants. Furthermore, a large capacity of the thermal energy storage, which is cheaper than battery storage, was the reason why it was easier to integrate a large share of variable renewables into the energy system. Having thermal energy storage in the energy system allows for more subtle ramp ups and downs of CHP plants in the time when PVs fulfil large share of electricity demand. Moreover, a large share of waste heat from waste incineration plants, which cannot be operated in a flexible manner [45], was also successfully integrated utilizing the DC system and thermal energy storage.

Other technologies that improved the flexibility of the energy system were reverse osmosis (RO) technology, V2G possibility, SOFC and SOEC coupled with the syngas storage, as well as load shifting possibilities (flexible demand) in industry and households. In the first three scenarios, an overcapacity of RO technology ranged from 2.1% to 4.6%. In the scenarios 4 to 6, the overcapacities were 9.5%, 8.1% and 5.8%, respectively. In the Scenario 7, the RO overcapacity was 0.1%, as other flexibility sources proved to be more economically beneficial. As RO technology consumes around 3.5 kWh_e/m³ of desalinated water produced, resulting overcapacities introduced a significant flexibility in the energy system. When low marginal cost electricity was abundant, excess RO operation could consume more electricity, and correspondingly produce more desalinated water than needed in a specific hour. On the other hand, when marginal electricity price was expensive, RO could operate with lower capacity and consume already stored desalinated water.

SOEC and SOFC technologies (along with the syngas storage) were utilized in the Scenario 7, the scenario with the lowest overall socio-economic cost and the largest share of variable PV generation. The installed capacities of SOEC and SOFC were 1826 and 434 MW, respectively. Both of those technologies introduced flexibility to the system as SOEC can be started when there is excess electricity supply in the system while SOFC can be utilized when there is a lack of power supply in the energy system. Although round trip electrical efficiency (power-to-gas-to-power) here was around 50%, one part of the heat energy can be recovered from SOFC and used in absorption units for the DC system, increasing the overall energy efficiency of those technologies.

The V2G possibility existed in all the scenarios, although large electrification of the transport sector occurred only in scenarios 4–6. In all the scenarios smart charge was anticipated, with the possibility of electric vehicles feeding the energy stored in their batteries back to the power grid when they were not utilized in the traffic. The most significant relative use of V2G possibility occurred in Scenario 3, the one with the large capacity of variable renewable energy generation and relatively small share of electrified transport. V2G use was also very frequent in the Scenario 7, the one in which both variable renewable energy generation and electrified transport reached very high levels.

Load shifting was utilized in scenarios 5, 6 and 7, the only scenarios where the load shifting was allowed. The load shifting in industry was utilized at 9% and 6% and 11% of the maximum potential in scenarios 5–7, respectively. In the households sector, it was utilized 5%, 3% and 6% in scenarios 5–7, respectively. However, it is very interesting to note that the load shifting in the case study in this paper actually increased the peak electricity demand. However, those peak demands correlated with the peak PV generation, meaning that the marginal costs of electricity production were still lower than in the case without utilizing the load shifting possibility. On the other hand, it is important to note that the

congestion in distribution grid was not modelled here, which could curb the possibility to increase peak electricity demand even more.

One can also note from the different storage capacities that the smart energy system seeks for integration of different storage types and there is not a winner-takes-it-all solution. However, it is indeed interesting to note that the optimal size of the PTES thermal energy storage was much larger than the battery storage in all the scenarios, except the BAU scenario that had no DC at all. Other important finding is that the optimal battery storage capacity of electric vehicles was much larger than the grid battery storage, in scenarios where the electrification of the transport sector occurred.

The air pollution, measured in terms of NO_x, SO_x and PM emissions, was much lower in scenarios 2–5 (except SO_x emission in scenario 3) compared to the BAU scenario. The latter was the consequence of significantly lower gas consumption due to increased energy efficiency within the system, as well as due to the electrification of the transport sector. However, in Scenario 6, in which CO_{2e} emissions were significantly constrained, biomass demand significantly increased. The latter caused a much larger air pollution than in the Scenario 4, showing that the sole focus on CO_{2e} emissions can worsen the air pollution issue. In Scenario 7, the large share of PV and solar thermal technologies resulted in much lower biomass demand than in the Scenario 6, significantly reducing the air pollution emissions. When discussing about the internalization of the negative health externalities, one should note that the air pollution costs were approximately 26 times larger in scenarios 1–3 than the mean of air pollution costs in scenarios 4–7. The latter shows that the non-point sources of air pollution, such as gasoline driven vehicles, have much larger negative externalities compared to the point source polluting generators.

Two different sensitivity analyses were carried out; the one on internalization of air pollution costs and the other on the consequences of the exclusion of import/export power capacity. As presented in Table 2, three different air pollution cost levels were calculated from the presented literature. As the middle cost rate was used in this paper, the sensitivity analysis was carried out by adopting low and high cost levels in Scenario 6. Implementing low and high air pollution cost levels did not have significant influence on the optimal technology mix in the energy system. However, it did have the influence on the total socio-economic costs of the energy system. Assuming low and high air pollution cost levels resulted in a total air pollution cost of 29 million € and 95 million €, respectively, compared to the 63 million € when middle cost rate was adopted. The latter resulted in a total socio-economic cost difference of energy system of ±1%, when using low and high air pollution cost levels. Thus, although adopting different air pollution cost levels can have significant influence on the total air pollution costs itself, the resulting difference in the total socio-economic costs of the energy system is much less pronounced.

Allowing import/export of electricity over the city borders was the other sensitivity analysis that was carried out. Up to 1650 MW of transmission capacity over the system boundaries was allowed in the system, following the potential future development of the ASEAN power grid [55]. The sensitivity analysis showed that the maximum possible transmission capacity would be invested in. Based on the runs for the Scenario 5, the total socio-economic costs would be lower 0.1%, capital costs would reduce for 0.6% while the total operating costs would increase for 0.4%. The analysis of the technology portfolio revealed that the import/export transmission capacity halved the needed capacity for the large-scale gas storage. It had further caused a significant decrease in the overcapacity of the reversible osmosis. The latter shows that the four flexibility possibilities presented in this paper can mutually compete and one must carefully optimize the energy system in order to avoid inefficiencies and suboptimal solutions. Capacities of other

technologies changed only marginally compared to the original Scenario 5.

Hourly operation of five different large scale storages (Appendix A) showed that none of the storages was utilized in a steady, intra-day pattern. The latter shows that one should be especially careful when decomposing the model using typical days, weeks or time slices in general. Case study developed in this paper shows that using typical time slices cannot realistically model different storages in an optimal way, as they do not have regular charging and discharging patterns in a complex system like the one modelled in this paper. The latter finding can be observed by following the hourly patterns of storage charging and discharging, presented in Appendix A.

Predefined technologies that were not economically feasible in the modelled energy system were, wind energy, waste heat from data centres coupled with heat pumps and natural gas and methanol synthesis from syngas.

Wind energy does not have suitable locations in Singapore in terms of wind speed, while waste heat from data centres coupled with heat pumps were prohibitively expensive considering the need for raising the very low temperature level of the waste heat (40 °C) to 95 °C and then utilizing it in absorption chillers with COP value of 0.7. Both natural gas and methanol synthesis options were not feasible enough (also including losses during syngas production and the final energy conversions of either synthetic natural gas or methanol) to be utilized in the system, compared to other available technologies such as electrified transport and biomass CHPs coupled with sea algae production.

In comparison with other studies that can be found in the literature, scenarios 2–5 showed similar DC penetration levels as the one anticipated for Dubai. In Dubai, with air conditioning responsible for 70% of final electricity demand, the city aims to meet 40% of its cooling needs through district cooling by 2030 [56]. In Ref. [57], it has been emphasized that the DC should first and foremost utilize natural cooling of rivers or sea, as well as the heat available from nature, such as geothermal energy. The former was not possible to be utilized in Singapore, due to the lack of any significant temperature difference of the air, ground or sea [7], while the latter was confirmed in the case of Singapore, as the maximum potential of geothermal energy was utilized in scenarios 2–7. As shown in the literature, smart energy systems were not researched in the tropical climate so far. However, they have been well researched for the colder regions. In Ref. [58], for the smart energy system in 2050, 50% of heat demand has been met by district heating, most of the transport sector has been electrified and energy efficiency of buildings has increased by 50%. Scenarios 2–5 from this paper showed similar district energy penetration levels, while energy efficiency in buildings reduced the cooling demand for 22.3% in scenarios 5–7. Majority of the transport sector in the city of Singapore was electrified, up to 98% in scenarios 4–7.

The author in Ref. [59] showed for the case of Denmark, that a smart energy system with 80% of electricity generated from renewable energy sources, PV should correspond to the 20% of the renewable electricity generated. In the scenario 7 from this paper, when PV capacity was not constrained by the space availability, 80% of the final electricity demand was met by variable PV generation. The latter points to the significant difference between modelling smart energy systems in tropical regions and smart energy systems in regions with colder climates, which have emphasized seasonality. The steady solar irradiation and the lack of seasonality, as well as steady cooling demand throughout the year, fosters much larger shares of variable PV generation compared to the colder climates.

The authors in Ref. [22] focused on the optimal mix between energy savings and district heat supply. They showed for the case of four different European countries that the thermal energy savings

in buildings should account for 0–60%, mainly based on the price of the available heat supply. In the case of Singapore from this paper, the heat savings in buildings accounted for 22.3%. The latter result is in line with [22], as Singapore had lots of heat available from CHP plants, geothermal and solar thermal energy, which made it cheaper to generate more cold than to invest large amount of funds for very large energy efficiency improvement in the buildings sector.

For the future case and the model development from the perspective of cities, it would be beneficial to integrate the industrial sector in the modelling of air pollution. Considering different case studies, better representations of energy efficiency options, technologies such as pumped hydro, concentrated solar power, wind and others could prove to be feasible. Moreover, integrating a smart water system into the model and optimizing pumping power, especially in a flat land like Singapore could further lead to increased efficiency of the whole energy system. Further focusing on the outlook of this study, it is important to mention that the expected population growth until the year 2050 will be highly uneven [60]. Almost all the population increase will occur in the Middle East, Latin America and Africa, majority of which will happen in the tropical region [60]. Hence, this case study is widely applicable to the other cities in the tropical region, in which population growth and economic development will significantly increase energy demand for cooling, transportation and other services. Thus, this paper represents a solid basis to initiate the discussion on potential of avoiding long term lock-in effects in the energy decisions that will significantly curb the potential for carbon and air pollution emissions control.

5. Conclusions

The research carried out in this paper showed that the integration of different energy sectors in the tropics can significantly reduce the socio-economic costs of urban energy systems, and at the same time provide cleaner air and mitigation of carbon emissions. The optimal smart urban energy system of Singapore included a certain share of district cooling, demand side management in industry and households, as well as in the water sector (reversible osmosis), energy efficiency measures in buildings, different storage technologies and renewable energy supply.

All the scenarios representing stepwise integration of the energy sectors showed significant socio-economic cost savings, reduction in CO₂e emissions and lower primary energy supply. In socio-economic terms, the best performing scenario (Scenario 5) resulted in 49% lower CO₂e emissions, 7% lower primary energy supply and 55% savings in the total socio-economic costs. The best performing scenario in terms of CO₂e emissions (Scenario 6) showed 46% lower socio-economic costs, 68% reduction in CO₂e emissions and 5% reduction in primary energy supply.

Air pollution was also reduced in all the alternative scenarios. However, in the scenario with the lowest CO₂e emissions (Scenario 6), air pollution was significantly larger than in the Scenarios 4 and 5, due to the increased use of biomass, which was modelled as CO₂e neutral technology in the energy system (all the biomass demand needed to be met by sea algae production).

A comparison between the cases when the energy system of the city seeks for achieving the self-sustainability and when it also utilizes the energy from its surroundings (Scenarios 6 and 7) showed that achieving the same CO₂e levels is cheaper by utilizing the energy from the city surroundings, too.

Future research on urban energy systems could further integrate water distribution system, including the needed pumping power for the water distribution, include job creation potential of different technologies, as well as behavioural economics of the demand side

of the energy system, to capture non-optimal decisions of the humans better.

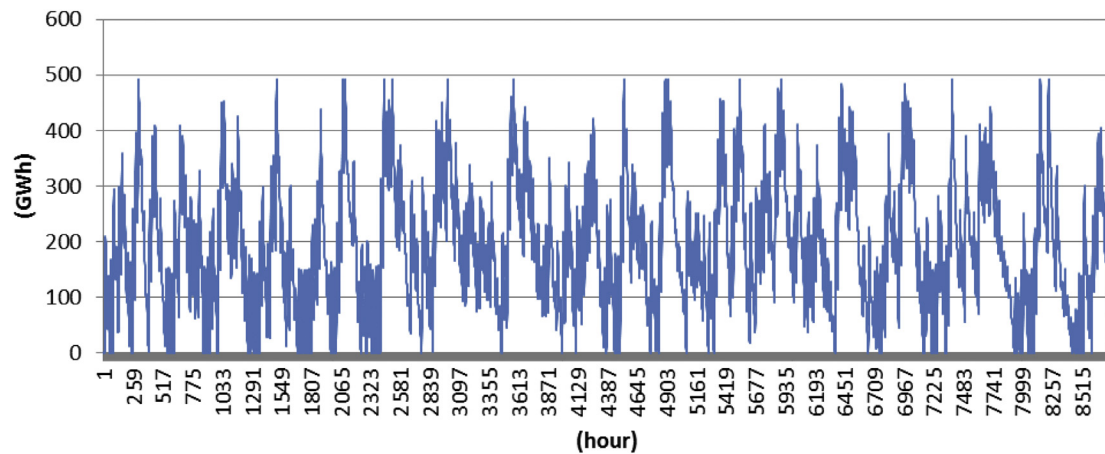
Acknowledgments

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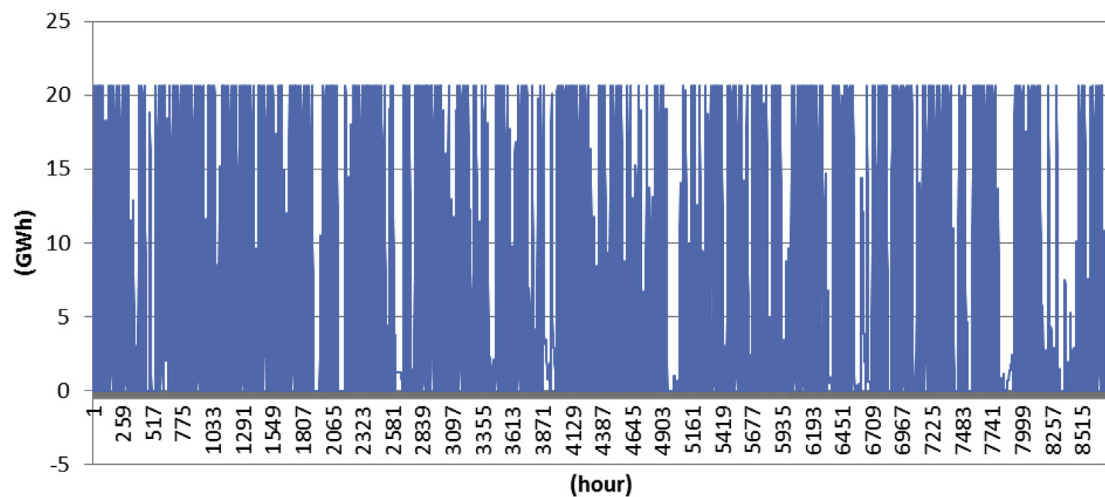
Appendix A

Hourly operation of different storages.

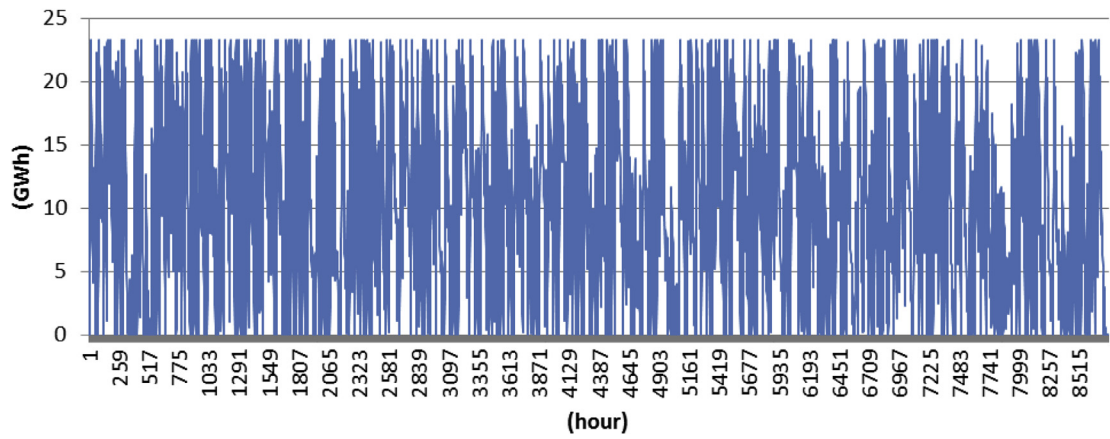
Pit thermal energy storage (PTES) level (Scenario 7):



Grid electric battery storage level (Scenario 7):

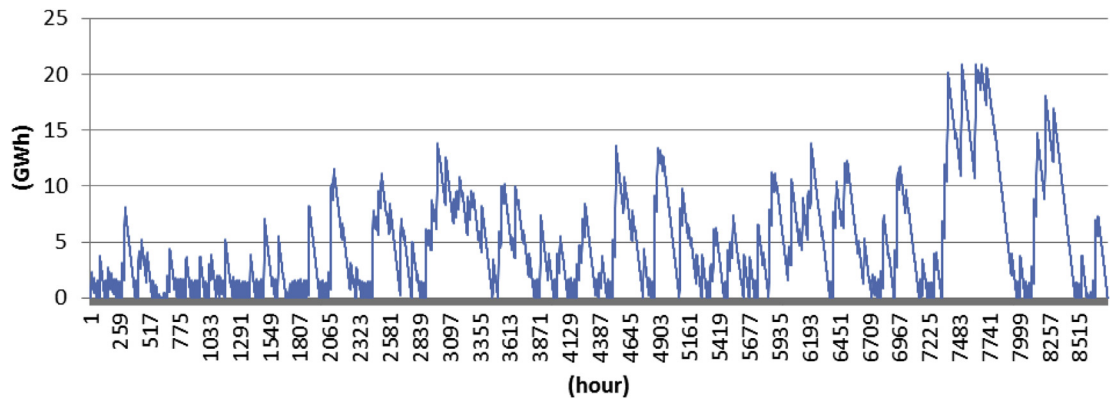
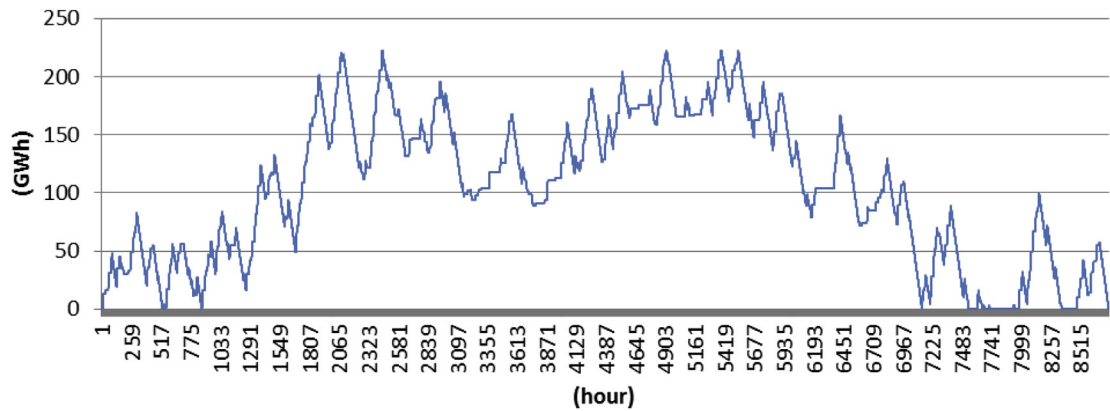


Electric vehicles batteries storage level (Scenario 7):



Syngas storage level (Scenario 7):

Gas storage level (Scenario 5):



Appendix B

Objective function:

$$DC_{demand} + ind_cool_{demand} \geq cool_{demand, total} - cool_{en,ef} \quad (B.7)$$

Absorption chillers energy balance:

$$\begin{aligned} \min Z = & \sum_{i=1}^n (fix_O\&M_i + lev_{inv_i})x_i + \sum_{j=1}^m \left(var_O\&M_j + \frac{fuel_j}{\eta_j} + CO2e_j \cdot CO2e_{inten_j} + air_poll_j \cdot air_poll_{inten_j} \right) x_j \\ & + \sum_{k=1}^p (gas_imp_exp_k + petr_imp_k)x_k + \sum_{l=1}^y inv_{en,ef,y} \cdot B_y \end{aligned} \quad (B.1)$$

Where levelized investment costs were calculated using Eq. (B.2).

$$lev_{inv_i} = inv_i \cdot \frac{dis_rate_i}{1 - (1 + dis_rate_i)^{-lifetime_i}} \quad (B.2)$$

Inequality constraints

Power sector balance:

$$x_{j,wasteheat,l} \geq (abs_{DC} / COP_{abs}) \quad (B.8)$$

Transport demand energy balance:

$$petr_{dem} + ele_{transport} \cdot C_1 + methanol \geq transp_demand \quad (B.9)$$

Syngas (hydrogen) balance:

$$\begin{aligned} SOEC - \frac{SOFC}{\eta_{SOFC}} - \frac{gas_{synthesis}}{\eta_{SNG}} - \frac{methanol}{\eta_m} + x_{j,syngas,storage_{dis}} \\ - x_{j,syngas,storage_{ch}} \\ \geq 0 \end{aligned} \quad (B.10)$$

Gasoline energy balance:

$$\begin{aligned} x_{j,EL,gas} + x_{j,EL,biomass} + x_{j,EL,other} + x_{j,battery,storage_grid_dis} + x_{j,grid_battery,storage_dis} + \\ SOFC - x_{j,battery,storage_{ch}} - x_{j,grid_battery,storage_{ch}} - \frac{chiller_{DC}}{COP_{DCchiller}} - \frac{chiller_{individual}}{COP_{individual}} - 0.1 \cdot \\ geothermal_{DC} - RO - \frac{SOEC}{\eta_{SOEC}} + flex - flex_{ch} \geq el_dem \end{aligned} \quad (B.3)$$

Gas demand sector:

$$petr_{imp} \geq petr_{dem} \quad (B.11)$$

$$\begin{aligned} x_{j,an_dig} + gas_imp + gas_{synthesis} + x_{j,gas,storage_{dis}} - x_{j,gas,storage_{ch}} \\ - \frac{x_{j,EL,gas}}{\eta_j} \\ \geq gas_dem \end{aligned} \quad (B.4)$$

District cooling energy generation balance:

Desalinated water production balance:

$$RO \geq water_{demand} \quad (B.12)$$

Capacity of technologies constraints:

$$x_j \leq x_i \cdot t \quad (B.13)$$

$$x_k \leq x_i \cdot t \quad (B.14)$$

Environmental constraints:

$$\begin{aligned} abs_{DC} + geothermal_{DC} + chiller_{DC} + x_{j,cold,storage_grid_dis} \\ - x_{j,cold,storage_{grid_{ch}}} \\ \geq DC_{demand} \end{aligned} \quad (B.5)$$

Individual cooling energy balance:

$$CO2e_{inten_j} \cdot x_j + CO2e_{intenk} \cdot x_{petrol} \leq CO2_{cap} \quad (B.15)$$

$$chiller_{individual} \geq ind_cool_{demand} \quad (B.6)$$

The share between the individual and district cooling demand:

$$\frac{x_{j,EL,biomass}}{\eta_{j,EL}} \leq algae_prod \quad (B.16)$$

Equality constraints

Electric vehicle battery storage energy balance:

$$\begin{aligned} \text{battery_level}_r &= \text{battery_level}_{r-1} + x_{j,\text{battery_storage_ch},r} \\ &\quad - x_{j,\text{battery_storage_dis},r} - x_{j,\text{battery_storage_grid_dis},r} \end{aligned} \quad (\text{B.17})$$

Heat storage balance equation*:

$$\text{heat_level}_r = \text{heat_level}_{r-1} + x_{j,\text{heat_storage_ch},r} - x_{j,\text{heat_storage_dis},r} \quad (\text{B.18})$$

Starting-end point storage constraint:

$$\text{heat_level}_1 = \text{heat_level}_{8760} = 0 \quad (\text{B.19})$$

*Syngas (hydrogen) storage, natural gas storage and battery grid storage were modelled in the same manner as the heat storage.

Energy balance for flexible demand in industry and buildings (shifted energy demand)

$$\text{flex} = \text{flex}_{ch} \quad (\text{B.20})$$

Building energy efficiency scenario (constraining that only one energy efficiency scenario can be chosen, as they are mutually exclusive):

$$\sum_{l=1}^y B_y = 1 \quad (\text{B.21})$$

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Paper 10 – Integrated energy systems of island countries

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Integrated energy planning with a high share of variable renewable energy sources for a Caribbean island

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Abstract: Although it can be complex to integrate variable renewable energy sources such as wind power and photovoltaics into the energy system, potential benefits are large, as it can help reduce fuel imports, balance the trade and mitigate the negative impacts in terms of climate change. In order to try to integrate a very large share of variable renewable energy sources into the energy system, an integrated energy planning approach was used, including ice storage in cooling sector, smart charging option in the transport sector and excess capacity of reverse osmosis technology that was utilized in order to provide flexibility to the energy system. A unit commitment and economic dispatch tool (Plexos) was used, and the model was run with both 5-min and 1-hour time resolutions. The case study was carried out for a typical Caribbean island nation, based on data derived from measured data from Aruba. The results showed that 78.1% of final electricity demand in 2020 was met by variable renewable energy sources, having 1.0% of curtailed energy in the energy system. The total economic cost of the modelled energy system was similar to the current energy system, dominated by the fossil fuel imports. The results are relevant for many populated islands and island nations.

Keywords: variable renewable energy; integrated energy modelling; Caribbean energy system; island energy system; smart charging; ice storage; oil imports; unit commitment and economic dispatch; energy system flexibility; flexible water desalination

1. Introduction

Following the Paris agreement, nations across the globe have decided to take actions to mitigate global warming by well under 2°C [1]. In order to achieve that goal, a significant reduction in greenhouse gas (GHG) emissions will need to be attained [2]. Renewable energy sources can achieve three different targets, reducing GHG emissions, providing a more affordable energy system in the long term, and securing energy supply, the three pillars of the European Union's plan for the energy transition [3]. The security of energy supply is especially important for islands and islanded countries, even more so if they do not have transmission connections with neighbouring countries. Currently, many island countries depend on GHG emission rich diesel generators, which leads to large consumption of fuel oil and diesel, and their associated GHG emissions [4]. Being heavily reliant

on oil makes the island communities especially sensitive to fluctuations in oil prices [5]. Currently, many islands have expensive oil-based energy systems in place, meaning that their transition towards cleaner energy systems does not necessarily need to result in a more expensive energy system in the long run, due to the rapidly decreasing costs of renewable energy technologies [6]. Furthermore, such communities can tackle the issue of security of energy supply by using energy sources that do not demand fuel, such as photovoltaics (PV) and wind turbines.

A comprehensive review of the modelling and planning of energy systems for isolated areas can be found in [7]. The authors showed that the most common software tools for modelling isolated areas were HOMER, H2RES, and EnergyPLAN to a lesser degree. In the mentioned review [7], papers being reviewed involved case studies focusing on the power sector and/or water sector only and not on the integrated energy planning across the whole energy sector. The most commonly used combinations of technologies were diesel-wind-PV with batteries and/or reverse osmosis (RO) for water desalination [7].

Some papers focused on the theoretical 100% renewable energy systems in islands, while others focused on the renewable energy supply in the power sector only. The EnergyPLAN tool was used to show that it is possible to achieve 100% renewable energy system on an island in Northern Europe by 2030 [8]. The authors stated that the renewable energy island would not be significantly more expensive than the business-as-usual case, having total system costs of 247 M€ per year for the renewable energy scenario and 229 M€ per year for the business as usual case. The authors adopted a holistic approach, integrating power, thermal and transport sectors at hourly time resolution; however, seawater desalination was not considered. Besides other technologies, the renewable scenario included a heavily electrified transport sector, where batteries were used to provide the grid flexibility via the vehicle-to-grid (V2G) technology, as well as different power-to-gas technologies. Variable renewable sources had a share from 33% to 68% of the total primary energy supply in different scenarios, while the remaining share was met by the biomass and biofuels combustion. Moreover, all of the alternative scenarios had a non-negligible amount of curtailed energy, in the range from 2% to 28%, the lowest amount being obtained in a scenario that included the large capacity of synthetic fuels production via electrolyzers and methanation processes. The scenario with the lowest primary energy consumption (6% reduction compared to a business-as-usual scenario) integrated all the energy sectors, including the total electrification of the transport sector with vehicle-to-grid utilization.

A similar methodology was adopted on a case study of a 100% renewable energy supply of La Gomera island for the year 2030 [4]. The modelling tool was again EnergyPLAN and the time resolution adopted was one hour. The power, heating, and transport sectors, as well as water desalination, were taken into account. The authors showed that based on their cost assumptions all of the alternative renewable scenarios had lower annual costs compared to the business-as-usual scenario. The most utilized technologies were PV, wind, electrolyzers and biomass power plants, while the storage technologies being utilized were batteries and hydrogen storage [4]. The share of variable renewable electricity generation was from 53% to 96.7% in different scenarios, while the remaining share was met by biomass combustion [4].

Fiji represents a small island developing state that is heavily dependent on imported fossil fuels. It produced 50.9% of electricity demand by diesel generators in 2014, with fuel import having a 21% share of total imports [9]. Thus, the authors stated that strategies for a quick transition to larger shares of renewable energy sources should be found in order to reduce the dependence on fuel imports [9]. As the authors carried out a SWOT analysis (strengths, weaknesses, opportunities, threats), they reported only yearly potentials of different technologies, without more detailed supply-demand analysis at finer temporal resolution.

Mauritius is an island with a population of around 1.2 million. As 50.7% of final energy demand is consumed by the transport sector, Mauritius is significantly dependent on imported oil [10]. Hence, the authors of [10] suggested a holistic approach when modelling a future energy system, including the transportation and cooling sectors. The authors of [10] presented the yearly potentials of different technologies citing many different sources, without a detailed supply-demand analysis at more

detailed time resolution. Another research group focused on the possibility of 100% renewable electricity on the island of Reunion by 2030 [11]. The authors used a TIMES model, having 8 hourly time slices for each day of a year [11]. The technical solution included 50% of variable energy sources, mainly solar and less wind and wave energy, while the remaining share was met by hydro and biomass [11]. However, the authors focused solely on the power sector and not on the whole energy system. Finally, Samsø island in Denmark achieved 100% net renewable electricity supply by a set of different energy policies and a significant inclusion of the local population in the transition [12]. Their technical solution included around 38% of primary energy demand met by variable renewable energy sources, mostly by wind, while other sources in the power sector included biomass and straw [12]. The scenarios for 100% renewable holistic energy system were carried out at hourly resolution, integrating the power, heating, and transport sectors [13].

Integrated energy modelling usually includes several or all the following sectors: power, heating/cooling, mobility, gas, and water [14,15]. A holistic energy modelling approach includes all the energy sectors, as opposed to a sole focus on a single sector, such as the power sector. It has been claimed that the cross-sectoral integration can achieve significant energy savings and result in a cheaper sustainable energy system [16].

The literature review presented here focused mostly on the future energy system in the medium and long-term. Moreover, a lack of the holistic approach focusing on the whole energy system can also be observed in the reviewed literature [7,11], with the power system often treated independently, and desalination infrequently included. On the other hand, papers that focused on the holistic energy system [4,8,13] focus on the short-term and used hourly time resolution. The latter resulted in viable models for energy planning purposes, but not for the operational planning, for which finer temporal resolutions are needed.

In order to tackle the problems identified in the literature, this paper aims to couple the comprehensive holistic approach in energy systems modelling with a finer temporal resolution (5-minutes) for a Caribbean Island case study, allowing for modelling at the operational level, rather than the planning level. Moreover, the resulting energy system is compared with the reference energy system in terms of levelized costs of electricity.

2. Methods

Energy Exemplar's Plexos software was used to model the energy system of the representative Caribbean island nation. Plexos is a simulation software that uses optimization techniques and a user-friendly interface to simulate the integrated electric power, and gas systems [17]. Plexos can implement a user-defined time resolution, providing the needed flexibility to the modeller. In this paper, a deterministic mixed integer linear programming approach was used with the objective function to minimize the total system operational costs. The Plexos modelling tool is a unit commitment and economic dispatch tool that can take into account different security, fuel and operational constraints. For the purpose of this paper, the focus was on the economic dispatch, and no security constraints were imposed that would take into account a possible sudden malfunction of a generator, voltage control and/or frequency regulation.

For this paper, 5-min and 1-hour resolutions were implemented in order to compare the differences in results when coarser and finer temporal resolutions were implemented. One year of operation of the energy system was modelled for the reference energy system, with a representative year chosen to be 2015, as well as for the near future energy system, with the modelled year chosen to be 2020.

The studied energy system integrated the power, cooling, transport, and water desalination sectors in order to absorb very large shares of variable renewable energy sources in the system. The driving force for this approach was the notion that much cheaper thermal energy storage (ice storage) can be used instead of more expensive grid batteries. Moreover, RO for water desalination can be operated flexibly, if sufficient overcapacity exists in the system, helping to match the electricity demand and supply. Furthermore, for a part of the transport sector that was anticipated to be

electrified by the year 2020, a smart charging option was assumed in order to further help the balance the demand and supply. Finally, the difference between vehicle-to-grid (V2G), where electricity can be fed to the grid from vehicle batteries when they are not used, and the smart charging option was compared in a sensitivity analysis.

In the power sector, PV, wind turbines, and gas power plants driven by biomethane extracted from landfills were prioritized for different reasons. First, both PV and wind energy do not contribute to air pollution (no emissions of NO_x, SO_x or particulate matter (PM)) or greenhouse gases (GHGs). Second, both PV and wind farms already exist on many of the Caribbean islands, making it easier to scale up the installed power, as the expertise already exists in the system. Third, waste disposal is a necessity in every country; thus, it is suitable to use it for energy generation in order to reduce the negative effects of landfilling. Fourth, both PV and wind turbines are rapidly developing technologies which have shown significant decreases in cost in the past several years [4]. The latter is beneficial for the economic feasibility of the energy system with large shares of renewable energy.

Based on the literature review, the two most widely used software tools for the modelling of islanded energy systems were H2RES and Homer [7]. The H2RES model follows a simple methodology of mapping the needs and resources and matching these two [18]. It has several pre-modelled technologies, such as wind, solar, wave, hydro, geothermal, biomass, fossil fuels, and desalination. Moreover, the model includes thermal storage, hydrogen storage, and batteries. It is simulation software that uses hourly temporal resolution. It has previously been mostly used for case studies in Portugal and Croatia [18].

Homer is a more flexible model compared to H2RES, with the possibility of modelling the power networks in much greater detail. Homer is focused on the power sector, with possibilities to model many different technological constraints particular to the power sector, and can implement the temporal resolution down to one minute. Due to its heavy focus on the power sector, the software has mostly been used for smaller technical systems such as microgrids or different combinations of PV or wind turbines combined with water desalination [7]. However, the Homer software is not particularly suited for modelling different storage solutions. It only has batteries as a predefined storage option. One workaround is that by suitably tweaking different battery characteristics, it is possible to model other types of storage, e.g. pumped hydro storage [19]. The objective of the Homer software is to find the least cost combination of equipment for microgrids for consistently meeting the electric load.

Plexos is a more flexible and comprehensive model compared to the both Homer and H2RES. It has flexibility in both temporal and spatial resolutions as the modeller can choose in how great detail it wants to model the transmission grid and load/generating characteristics. Moreover, Plexos has well developed general storage solutions which can easily be adopted for any storage that generates or consumes electricity.

In this paper, the part of the transport sector that was electrified was modelled via batteries located in electric vehicles. A smart charging option was utilized, meaning that the vehicles could be charged in an optimal way from the system point of view, as long as they are parked and connected to the grid. The hourly transport demand pattern was taken from [20], while the transport energy demand for the typical Caribbean island country was taken from [21].

Thermal storage (ice storage) can provide a load shifting possibility in the system, as the ice can be generated when there is an abundance of electricity generated in the system and then utilized when there is a lack of low marginal cost electricity available in the system. Ice storage was modelled as storage that can be filled at any point of time. The energy can then be discharged to meet the cooling loads in the system. The discharge of the storage was constrained up to the maximum amount of the cooling demand in a particular hour or 5-minute period. However, the cooling demand could have been met by direct utilization of electricity in electric chillers, by ice storage, or by a combination of both. The latter combination was allowed to cover the possibility that due to the large installed capacity of PV, the excess electricity could be generated during the midday when the cooling demand is usually the largest. There were no implemented constraints on the number of cycles that chillers could perform in a year. The cooling pattern for hotels in hot regions was adopted from [22] while

the amount of energy demand for cooling of hotels and resorts in a typical Caribbean island nation was taken from [21].

Finally, RO technology for water desalination and the associated desalinated water storage was the third modelled *storage* in this paper. RO can be run flexibly if the excess capacity exists in the system. The typical Caribbean island nation can have more than 38% of excess capacity for the desalination of seawater [23]. As the average consumption of electricity per m³ of desalinated water produced by RO technology is around 3.5 kWh, RO technology can be considered as storage if more desalinated water is produced when there is excess electricity available in the power system, and then stored in relatively cheap desalinated water storage. The equivalent of three days of storage of desalinated water was assumed in this study to increase the flexibility of the energy system. The approach of using water storage instead of energy storage was also adopted in [24], although their storage size was much larger, equating to 30 days of water demand. On the other hand, for the case of flexibly utilizing reverse osmosis for the case of Jordan, the storage capacity equated only to 6h of average demand [25]. For this paper, it was assumed that smaller the capacity of three days of average water demand would provide enough flexibility in the energy system.

3. Case study

The case study used in this paper depicts a typical island nation in the Caribbean, and is based on data derived from measured data from Aruba. Our case study consists of a single island nation with a population of approximately 100,000. The yearly electricity consumption in the reference year (2015) was 657.5 GWh, while the peak load demand equals 99.5 MW. Almost all the fossil fuel primary energy demand is in different forms of oil, i.e., diesel, gasoline, and fuel oil. All the oil used in the energy system is imported, putting a significant burden on the current account balance of the island country. One can assess the share of oil demand in different sectors in Table 1. Electricity generation is responsible for 75% of the total oil demand.

Table 1. Primary energy demand for the representative Caribbean island

Oil consumption	GWh/year	Share
Electricity generation	3,141	75%
Transport	743	18%
Industry	304	7%
Total	4,188	

Current power plants are driven by distillate fuel oil, consisting of back-pressure steam turbines, combustion turbines and reciprocating engines, along with the wind turbines and PV. One can note from Table 2 that the number of generators decreased in terms of steam turbines and combustion turbines. The most demanding part would be to find suitable locations for another two onshore wind plants. This could possibly be solved via significant upgrades of the two currently used sites.

Load demand is expected to remain constant through the year 2020 due to increased energy efficiency measures. Hence, an increase in economic activity was assumed to be balanced by the increased energy efficiency measures, resulting in flat electricity demand.

In order to project a realistic energy system for the short-term future, it is important not to significantly increase the number of energy generator sites, as the latter can significantly complicate the projects due to sitting and permitting issues.

Table 2. Number of generator units and the total installed capacities in 2015 and 2020*

	Reference system 2015 (MW)	Energy system 2020 (MW)
Steam turbines	4 (69)	3 (46)

Reciprocating engines	6 (30)	6 (30)
Combustion turbines	5 (40)	4 (30)
Solar PV	1 (8)	2 (50)
Wind	2 (50)	4 (100)
Gas turbine (biomethane)	0	1 (10)

* For PV and wind plants the stated value represents the number of locations. The total capacities are stated in brackets.

Installed capacities of the different technologies can be found in Figure 1. The total capacity of ice storages was 820 MWh, with 30 MW of power in a pumping mode and 15 MW in a discharge mode. Reverse osmosis had a capacity of 44,000 m³/day, equivalent to the peak power demand of 6.4 MW.

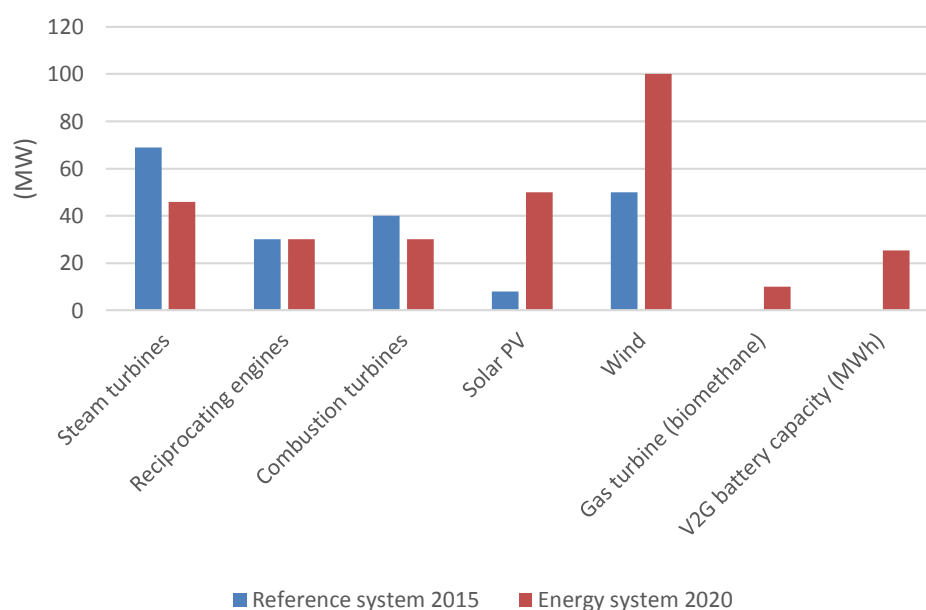


Figure 1. Installed capacities of different technologies in the year 2015 and 2020

Typical transport distribution between different modes for a Caribbean island nation dominated by tourism can be seen in Table 3. Buses, tour buses and taxis (noted with bold font) are the transport modes that could be quickly electrified via governmental policies. Moreover, those transport modes usually operate significantly more frequently than personal vehicles, which could bring additional savings to their operational costs. The transport modes anticipated to be electrified represent 11.9% of the final transport energy demand.

Table 3. The share of different transportation modes in a typical Caribbean island [21]

	Number	Fuel type	total gallons per day	Share	GWh/year
Passenger cars	24991	gasoline	15446	28.0%	204
Passenger vans (gasoline)	17493	gasoline	14788	26.8%	195
Passenger vans (diesel)	4806	diesel	2844	5.2%	40

Trucks	901	diesel	10030	18.2%	141
Buses	116	diesel	2409	4.4%	34
Tour buses	173	diesel	1497	2.7%	21
Taxis	373	gasoline	2557	4.6%	34
Rental	3620	gasoline	4648	8.4%	61
Government vehicles	448	gasoline	383	0.7%	5
Motorcycles	1791	gasoline	610	1.1%	8
Total			15446		743

Economic input consisted of the investment costs of the energy plants, fixed and variable operating and maintenance (O&M) costs and fuel costs. Socio-economic costs of the energy system were calculated and reported, meaning that the taxes were not included. A potential carbon tax [26] and the resulting costs were separately reported in the sensitivity analysis in order to allow for the comparison if the negative externalities caused by the climate change are to be included in the socio-economic costs. The economic parameters used in this study can be seen in Table 4.

Table 4. Economic parameters used in the study

	Investment cost (USD/MW)	Fixed O&M (USD/MW)	Variable O&M (USD/MWh)	Efficiency	Technical lifetime (year)	Ref
Steam turbines	1,500,000	45,000	4.25	26%	30	[27]
Reciprocating engine s	1,430,000	0	9	42%	25	[28]
Combustion turbines (mini size, 0.1-5 MW)	1,750,000	0	7	29%	25	[29]
Wind turbines	1,384,000	22,000	0		20	[30]
Photovoltaics	1,450,000	14,000	0		30	[30]
Biomethane (gas turbine, medium size, 5-40MW)	1,400,000	0	4.25	40%	25	[29]
Desalination plant (USD/m ³ /day)	800	40	0		25	[31]
Ice storage (USD/MWh)	10,000	250	0	90%	25	[27]

The distillate fuel oil price that was used for the year 2020 was 5.43 2015USD/MWh_{fuel}, while the price forecast was obtained from the US Energy Information Administration [32]. Possible carbon tax for the year 2020 was set at 15 USD/tonCO₂, based on [26]. The weighted average cost of capital (WACC) that was used for the economic calculations was 7%.

Based on [21], it was assumed that 15% of the total electricity consumption over the year goes toward cooling of hotels and resorts in the Caribbean nations. It was assumed that the same share of the peak load is demanded by the cooling systems of hotels and resorts. Hourly cooling distribution was adopted from [22], that was made for the case of Singapore, which also has steady temperatures without distinctive seasons over the year. The total capacity of thermal storage (ice storage) was set to the equivalent of three days of cooling demand, i.e., to 0.8 GWh. The heat exchangers could deliver 15 MW of cold in the discharging mode and store 30MW of cold in the charging mode.

In total 88.5 GWh of yearly oil demand for transport (11.9% of the total oil demand for transport) was electrified, as it was assumed that buses, tour buses and taxis could quickly switch to electrified

means, due to the large operational times and thus, large potential operational savings when electrified. Due to the increased efficiency of electric motors compared to the internal combustion engines, it was assumed that the buses would become more efficient by a factor of 2.5 [33,34] and taxis by a factor of 3.5 [35]. The resulting final electricity demand for the same transport demand amounted to 30.7 GWh/year.

It was assumed that the consumption of buses is 1.35 kWh/km [33] and the consumption of cars is 0.2 kWh/km [35]. Battery capacities were 320 kWh per bus and 100 kWh per car (taxi). Buses were charged via 150 kW chargers and cars via 100 kW chargers. The resulting capacity of batteries in all the electrified vehicles in the year 2020 was 21.3 MWh for the case of buses and 4.1 MWh for the case of cars.

The main economic indicator for the energy system was the total socio-economic cost of the system, while the technical indicators were fossil fuel consumption, total primary energy supply, curtailed energy, and needed dispatchable power sources in the system for the case when neither wind turbines nor PV were generating electricity. Total CO₂ emissions were the environmental indicator of the energy system.

4. Results

The energy system was simulated via the Plexos model built from the data described in Section 3, finding the cost-optimal generation mix, resulting in the minimized operating costs of the energy system. The total load demand and curtailed energy on both 5-minute and 1-hour time resolutions, as well as the primary energy supply in the energy sector, can be seen in Table 5.

Table 5. Technical indicators of the energy system

	2015	2020
Peak demand (MW) 1h	93.6	109.4
Peak demand (MW) 5min	99.5	110.6
Total generation (GWh)	657.5	699.0
Curtailed energy 1-h (GWh)	0	0.5
Curtailed energy 5-min (GWh)	0	7.1
Wind (GWh)	237.9	461.5
PV (GWh)	17.81	98.4
Oil* for power sector (GWh)	1273.2	305.8
Oil* for transport and industry (GWh)	1047	939
Primary energy supply (GWh)	2575.8	1805.1

* All of the oil consumption was imported

One can note from Table 5 that curtailed energy is significantly greater with the 5-minute resolution than with the 1-hour temporal resolution. The reason is that the sudden spikes in the energy generation from the variable energy sources are averaged out in the 1-hour resolution data, not revealing the true amount of the curtailed energy. It is important to note that in the Caribbean both PV and onshore wind turbines have high capacity factors, i.e., 54.1% for wind turbines and 25.3% for PV in this case study. The total curtailed energy with the 5-min resolution data for the year 2020 was equal to 1.0% of the total generated electricity.

For the energy system in the year 2020, PV met 14.5% of the total electricity demand, wind met 63.6% of the total electricity demand and the biogas power plant met 6.5% of the total electricity demand. Therefore 78.1% of the total electricity demand was met by variable renewable energy sources and a total of 84.6% of electricity demand was met by renewable energy sources. The shares of steam turbine plants, combustion turbine plants and reciprocating engines electricity generation were 4.8%, 0.1% and 10.6%, respectively.

Electric vehicles consumed a total of 30.7 GWh of electricity (11.9% of the end-use transport demand and 4.4% of the total electricity generation), and all of the energy demand was met via smart charging. Excess capacity of the RO for water desalination used the 0.9 GWh of electricity in a flexible manner (0.13% of the total electricity generation), acting as a flexible load for the grid. Ice storage provided 19.16 GWh of chilling to the hotels and resorts, equivalent to the 19.4% of the total cooling demand of the hotels and resorts. The remaining amount was met by direct utilization of electricity in electric chillers.

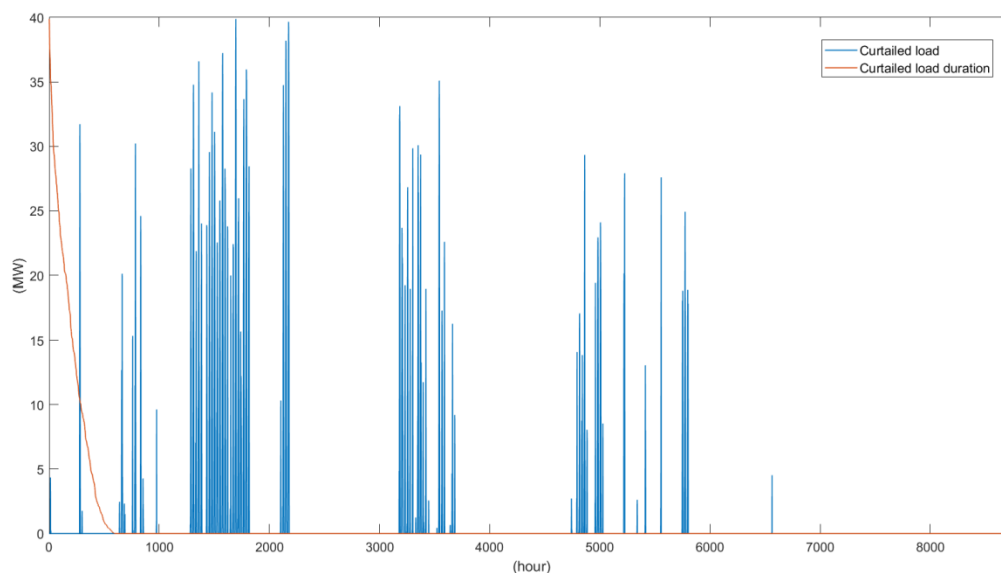


Figure 2. Curtailed energy in the energy system of 2020

The curtailed energy in the hours of the occurrence, as well as the curtailed load duration representation, can be seen in Figure 1. It can be seen that the curtailed energy occurred during a small number of hours, but at very high levels. Curtailed energy occurred during 5.3% of the yearly 5-min intervals.

The maximum dispatchable power needed on the 5-minute time resolution was 98.5 MW or 89% of peak load of the system. Although there were 104 hours when neither wind turbines nor PV were generating electricity, the dispatchable power needed was lower than the peak load due to the mismatch in peak load demand and periods without any generation from variable sources, as well as the ability of thermal energy storage to cover part of the cooling load instead of using electricity directly in chillers.

The total system costs are presented in Figure 3. The levelized costs of the energy system (carbon costs excluded) were 2.2% higher in the year 2020 than in the year 2015. On the other hand, the socio-economic costs of the energy system (carbon costs included) were 2.5% lower in the year 2020 than in the year 2015.

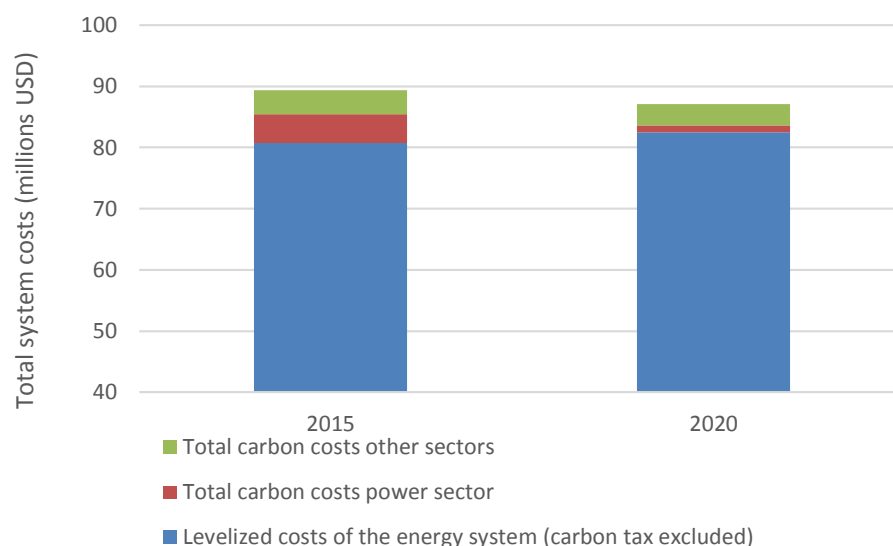


Figure 3. The total system costs of energy systems in 2015 and 2020 (note that y-axis does not start with zero)

Detailed economic results of contributing costs of different parts of energy system in the overall costs can be seen in Figure 4. One should note that only the costs of the transportation that underwent electrification are presented in Figure 4 as the costs for other vehicle types did not differ between the two compared energy systems.

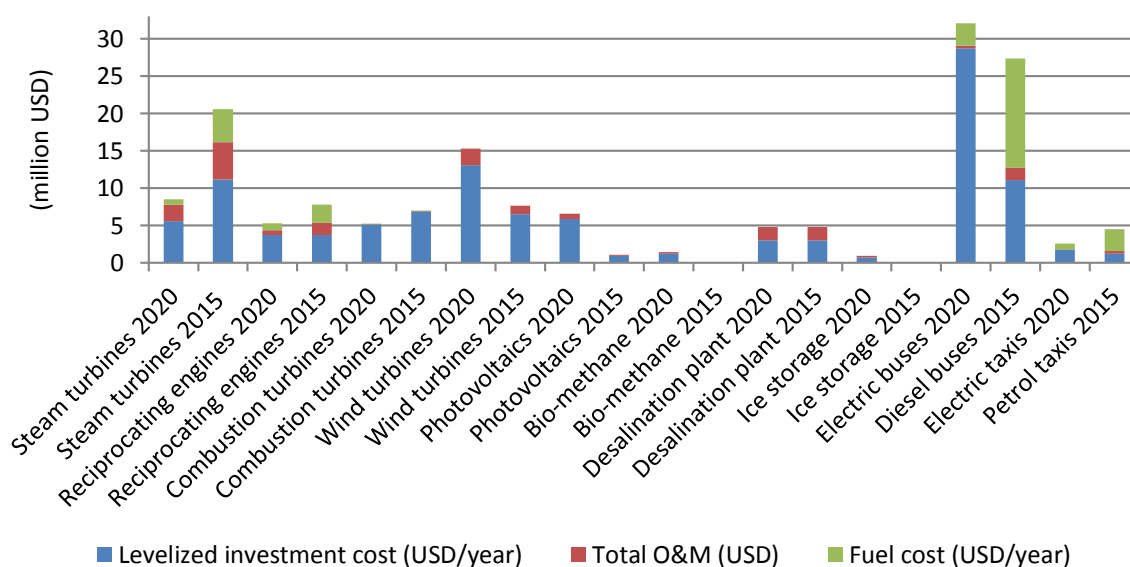


Figure 4. Economic results (carbon costs excluded) of the energy systems in the reference year and the year 2020

A sensitivity analysis was carried out in order to check the impact of potential V2G charging concept versus smart charging. The sensitivity analysis was carried out with the 5-min temporal resolution data. The amount of curtailed energy was 7.01 GWh in the V2G case, versus 7.12 GWh in the smart charging case. The V2G option managed to integrate only marginally more renewable energy sources, 84.7% to 84.6%. Hence, it can be concluded that smart charging is sufficient for the penetration levels of variable renewable energy sources assumed in this case study. The latter could be an important finding as many vehicle manufacturers could be hesitant to allow for higher cycling of vehicle batteries that would be needed if the V2G option would be utilized.

Another sensitivity analysis was carried out in order to check the sensitivity of the fossil fuel based energy system on the price of oil. As it can be seen from Figure 3, the levelized costs of the energy system (without carbon tax included) were 2.2% higher for the renewables-based energy

system than the fossil fuel based energy system. The sensitivity analysis showed that the fuel price increase of 7.3% compared to the prices reported by the US Energy Information Administration [32] would be needed to reach the price parity of both energy systems in terms of levelized costs (carbon tax excluded).

The CO₂ emissions of the energy sector, transportation and industry can be seen in Table 6. Carbon emissions in the power sector were reduced by 76% in 2020 compared to the reference system. The total carbon emissions were reduced by 46% in the year 2020 compared to the energy system of the reference year.

Table 6. CO₂ emissions in the energy system

	2015	2020	Unit
Carbon emissions power sector	317,000	76,000	tonCO ₂
Total carbon emissions (including industry and transport)	578,000	311,000	tonCO ₂

5. Discussion

Using integrated energy modelling approach in this paper, the energy system with a significant amount of variable renewable energy was achieved at a cost similar to the traditional, fossil fuel-based energy system in the Caribbean. Moreover, it was shown that when a significant amount of variable energy is modelled in the system, a sub-hourly temporal resolution is needed in order to realistically capture the curtailed energy. Furthermore, it was shown that the energy system could significantly change in the near future with existing technology solutions.

Generally, there are four main flexibility sources in an energy system; transmission capacity to neighbouring areas for import/export of electricity, energy storage, demand response and power-to-heat or power-to-gas technologies [36]. In this paper, the value of energy storage and power-to-heat flexibility sources in meeting carbon and fuel reduction goals were investigated. It is important to note that no grid battery storage was installed, while still integrating very large shares of variable renewable energy in a competitive manner.

Also important to note is that the ice storage is significantly cheaper than the battery storage and this fact was successfully utilized in the modelled energy system [37]. Although the battery prices have dropped significantly in the last decade, and even if the positive trends continue, the resulting prices of different battery types are anticipated to be in the range of 100–200 USD/kWh [38]. Compared to the ice storage prices of 10USD/kWh (Table 4), one can note that the future prices are expected to be at least one order of magnitude lower compared to the prices of battery storage. The latter points to the importance of integrated modelling of the power and cooling sectors, and more broadly heating, ventilation and air conditioning (HVAC), in order to make it possible to utilize the lower CAPEX costs of thermal energy storage technologies.

The achieved curtailed energy in this paper was 1.0% of the total generated electricity, which is a lower amount than given in [39], where the 5% threshold was achieved. Moreover, on one of the resulting charts from [8], it could be seen that all the future scenarios modelled for the Åland Islands had between 2% to 28% of the energy curtailed, a much larger amount than in the present paper. Furthermore, this case study generated 78.1% of electricity from the variable energy sources, compared to the 38% for the case of renewable Samsø island [12] and around 50% for the case of renewable Reunion island [11]. Finally, the local integrated energy system without the import/export transmission capacity achieved a 57% share of variable renewable energy generation, without the reported curtailed energy (modelled on 1-hour temporal resolution) [40].

The transport sector can play an important role in providing flexibility when electrified. One paper that used the same modelling tool as in the present paper showed that the smart charging of vehicles does not cause increased peak load for the case of Ireland [41]. In this paper, the electrified part of the transport sector successfully provided the flexibility needed for the integration of a significant amount of renewable energy sources. Furthermore, the difference between smart charging

and V2G mode was only marginal, i.e., the amount of curtailed energy reduced by 1.5% in the case of V2G operational mode (from 7.12 GWh to 7.01 GWh). However, keeping in mind that the total curtailed energy of the energy system of 2020 amounted to the 1.0%, the resulting difference between smart charging and V2G is not significant.

Finally, oil imports could be significantly reduced by adopting the proposed measures in the energy sector. The resulting oil imports for the power, transport and industry sectors in 2020 would be 46.4% lower than in 2015 (Table 5). Reduced oil imports would improve the balance of payments, as well as increase the generation diversity. Furthermore, a shift towards more capital intensive renewable energy sources would shift the burden of operational costs from variable cost, dependant on the changing fuel prices, to fixed costs, which can be planned for in advance. Moreover, the holistic energy modelling and resulting measures, as well as the achieved lower reliance on the imported oil for the typical Caribbean island nation is in line with the recommendations made for Mauritius [10].

There are several limitations of this study. First, the adopted 5-min temporal resolution is still not fine enough for modelling frequency and voltage control, which could impose further costs on the power system. Second, the transmission and distribution grids were not modelled, resulting in a lack of possibility to capture grid congestion which could further curtail a certain amount of renewable generation. Third, due to the lack of available data, industry consumption data was not optimized in the system, meaning that there are probably additional efficiencies that could have been captured. Fourth, only the socio-economic costs were reported, which lacks the detailed business-economic analysis needed if the push for more PV and wind energy would be achieved by private investors. Fifth, air pollution and the corresponding negative externalities were not captured by this model. Although one can argue that more wind energy and PV will emit less harmful emissions and pollutants (NO_x, SO_x and PM) compared to the oil-driven technology, the latter difference was not quantitatively calculated by this model. The limitations mentioned here represent possible future research directions that could further improve energy planning of the island countries, especially for those located in the hot regions, like the ones in the Caribbean.

As globally more than 11,000 inhabited islands can be found, with a population of around 740 million people [40], the results of this study are relevant for many different case studies, especially those of developed countries in tropical regions. Furthermore, the results of this study are relevant for any energy system with large cooling demand, which is not connected to the surrounding regions via transmission cables.

6. Conclusions

An integrated energy modelling approach for a Caribbean Island case study was carried out in this study. The study focused on the energy transition in the short-term, taking into account the power, transport, cooling, and water desalination sectors. Moreover, the study focused on the operational planning of the energy system with a large share of variable renewable energy sources, adopting 5-minutes time resolution. Several conclusions arose from this study:

- Integrated energy modelling allowed for integration of large share of variable renewable energy sources, i.e., 78.1% of the final electricity demand was met by variable renewable energy sources, with 1.0% of curtailed energy in total, although the modelled energy system did not have external transmission capacity with the surrounding regions.
- Vehicle-to-grid (V2G) charging option had only marginally better results in integrating variable renewable energy sources (measured by reduction in curtailed energy) than the smart charging option, reducing the amount of curtailed electricity generation by only 1.5% (from 7.12 GWh to 7.01 GWh).
- The energy system based on variable renewable energy sources had a similar economic cost compared to the incumbent, fossil fuels based energy system. The renewable energy system was

2.2% more expensive than fossil fuels based energy system, excluding the costs of CO₂ emissions. In terms of socio-economic costs of the energy system (carbon costs included), the renewable energy system was 2.5% cheaper than the fossil fuel based one. One of the sensitivity analyses showed that fossil fuel prices would need to increase by 7.3% in order for levelized costs of the renewable energy system to reach the price parity of the fossil fuel based energy system.

- Oil imports could be reduced by 46% in this case study, potentially reducing the negative current account balances for small island nations
- A large number of inhabited islands worldwide (more than 11,000 with approximately 740 million inhabitants) makes the result of this study relevant and transferable to other case studies located in the warm regions

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